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Review

Adopting extended reality? A systematic review of manufacturing training and teaching applications

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ABSTRACT

The training of future experts and operators in manufacturing engineering relies on understanding procedural processes that require applied practice. Yet, current manufacturing education and training overwhelmingly continues to depend on traditional pedagogical methods that segregate theoretical studies and practical training. While educational institutes have generally improved theoretical studies, they often lack facilities and labs to properly reproduce the working environments necessary for practice. Even in industrial settings, it is difficult, if not impossible, to halt the actual production lines to train new operators. Recently, applications with extended reality (XR) technologies, such as virtual, augmented, or mixed reality, reached a mature technology readiness level. With this technological advancement, we can envision a transition to a new teaching paradigm that exploits simulated learning environments. Thus, it becomes possible to bridge the gap between theory and practice for both students and industrial trainees. This article presents a systematic literature review of the main applications of XR technologies in manufacturing education, their goals and technology readiness levels, and a comprehensive overview of the development tools and experimental strategies deployed. This review contributes: (1) a state-of-the-art description of current research in XR education for manufacturing systems, and (2) a comprehensive analysis of the technological platforms, the experimental procedures and the analytical methodologies deployed in the body of literature examined. It serves as a guide for setting up and executing experimental designs for evaluating interventions of XR in manufacturing education and training.

1. Introduction

While virtual reality (VR) systems have existed as research prototypes since the 1960s (Sutherland, 1965, 1968), the advent of commercially available robust hardware and software is relatively recent. The first affordable head-mounted display (HMD) for accurate and real time VR navigation was the Oculus Rift launched to market in 2016 [1] with development kits and peer-reviewed research papers as early as 2014 [2,3]. Furthermore, while augmented reality (AR) systems have existed as tailor-made research projects since the 1990s [4], once again, commercially available AR hardware and software became commonplace only in 2018 with the near-simultaneous release of Google's Android AR Core and Apple's AR Kit [5]. Milgram and Kishino [6] describe a virtuality continuum that ranges from the real environment to the virtual. On this scale, AR sits between both ends, but closer to the real environment than virtual reality. The virtuality continuum, also known as the reality-virtuality continuum, is the spectrum of immersive interactive technologies ranging from reality to virtual reality (see Fig. 1). While many authors have defined this spectrum, we focus on the original and most widely used definition by Milgram and Kishino in 1994 [6]. The spectrum starts with reality on one end, where interaction happens with physical objects. These objects may include 3D printed artifacts, tools, robots, actuators, and so on. Extended reality (XR) can be considered the widest artificial representation of the world in the reality-virtuality spectrum (see Fig. 1).

To investigate the broader impact that XR technologies might have on education, in general, and on education and training in manufacturing engineering, in particular, we must contextualize the technological environment of the field. Widespread and deep impact is only possible once the technologies mature to the point of affordable and robust systems. Furthermore, we must take into consideration the impact of the COVID19 pandemic on learning and working. Most of the world's population has studied and worked at a distance for most of 2020 and 2021. In this environment, the need of immersive telepresence technologies has been made dramatically evident. The issues raised by the pandemic

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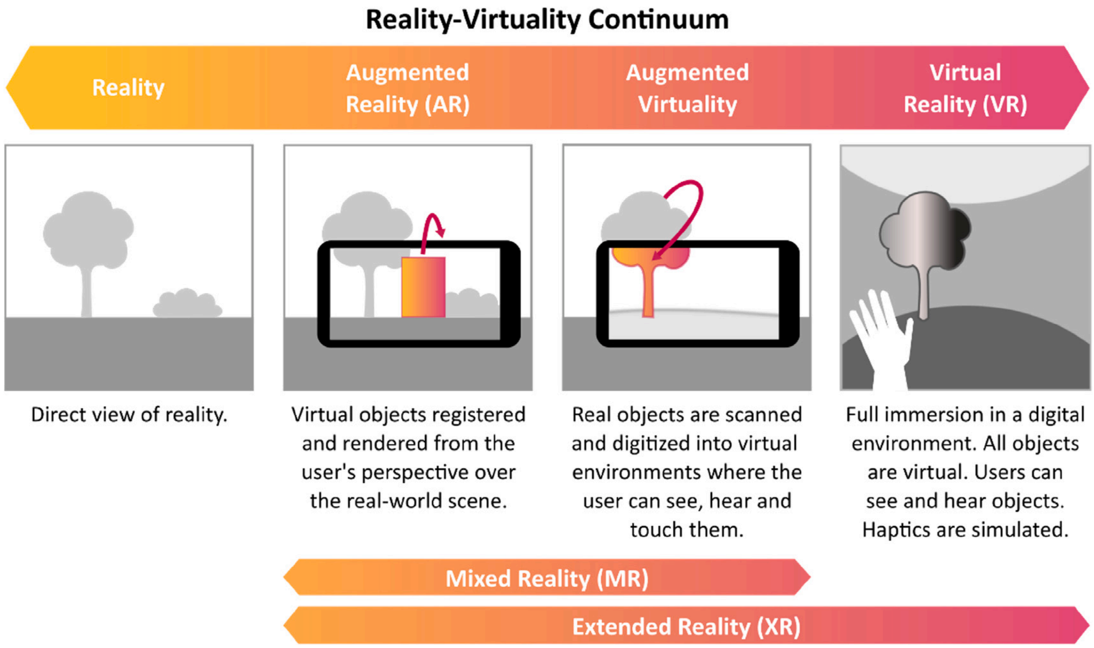

Fig. 1. Reality-virtuality continuum, ranging from reality to virtual reality (VR). Intermediate dimensions are augmented reality (AR), mixed reality (MR) and extended reality (XR).

have forced many companies across the whole word to re-think their teaching and training strategies. Availability and use of resources as well as capability to ensure accessibility for the learner are amongst the main challenges. While teleconferencing solutions such as Zoom, MS Teams, Google Meet and Skype provide a proper replacement channel for face-to-face communication, "shoulder-to-shoulder" collaboration requires sharing first-person perspectives across the medium.

Blended learning (BL), or hybrid learning, which combines the best of online education and traditional face-to-face interaction, has been emerging since before the pandemic as a tool to address these challenges [7], and it can heavily encourage the implementation of XR technologies for learning processes that require shared immersion [8]. Teleconferencing systems do not provide this functionality. While users may adapt to get the most out of the communication channel, only AR and VR technologies are particularly suited for this mode of collaboration between humans who are focused on sharing not just declarative knowledge, but, more importantly, procedural knowledge [9]. The main difference between the two is that while declarative knowledge can describe a static environment, e.g., a stationary system, procedural knowledge comprises of both actions and declarative knowledge with respect to time [10,11], thus allowing the description of dynamic environments, e.g., the execution of manufacturing tasks.

In this paper we present a comprehensive review of the existing publications applying XR technologies to the teaching and training of manufacturing engineering, a field particularly centered on procedural knowledge, that is, the know-how of the step-by-step procedures combining theoretical and practical expertise. We present a review of the publications that have passed our acceptance criteria. We have only included papers with a clearly communicated experimental design and execution of human-subject user studies with learners in manufacturing using XR technologies.

The overall outcome of this study is therefore to categorize the recent literature, examine the state-of-the-art solutions and highlight the key benefits of such technologies in this framework. It is interesting to evaluate how technologically ready higher education institutes and the industrial world are to embrace the digital environment as a reliable tool for learning. With this work we want to investigate how XR technologies can be a support to enhance the learning process itself, and we feel that our contribution can also give a decisive push to the growth and diffusion of the BL trend.

With a preliminary study of the existing literature, we noted that research in this field is scattered and not cohesively formulated. In particular, the quantitative data related to the studies are often missing, and, when present, are not homogeneous enough to establish the basis of the literature analysis. Given this gap in the identified contribution, and in order to still gather insights from it, we focused on a more qualitative approach, based on deep analysis of the semantics of the presented content. In detail, looking at the available descriptive sections of the selected articles, we: (1) highlight the goals of each existing XR application in manufacturing education; (2) list all the development tools identified. In addition, by looking at the nature of the studies, an additional outcome is to (3) compare the different adopted experimental methods. This, in turn, allows to get a feeling of the readiness level of each application, so that it makes possible to (4) propose an estimation of it within the body of knowledge analyzed. These research objectives are reflected in the following research questions:

- **RQ1:** What are the existing applications and their goals?
- **RQ2:** What are the main development tools used?
- **RQ3:** What are the main experimental strategies applied?
- **RQ4:** What is the technology readiness level of the applications?

The remainder of this article is organized as follows. Section 2 presents a summary of other literature reviews and other works related to the discussed topic. Section 3 details the research methodology that we adopted for this review article. Section 4 contains the results of our literature review, including descriptive statistics and qualitative analysis. In Section 5, we discuss any related scientific and practical implications and we indicate potential future research. Our final conclusions are in Section 6.

2. Related works

This section presents the literature reviews of related works. It highlights the main similitude and the shortcomings. Before proceeding, it is relevant to provide a brief account of two review papers that we excluded from our results. Bottani and Vignali [12] reviewed articles published from 2006 to 2017, about how AR technologies are applied in industry: the applications are experimental prototypes, showing potential in many areas of industry. Doolani et al. [13] focused their work on how the manufacturing workforce training is influenced by exploitation of XR technologies, and it refers to articles published between 2001 and 2020. The first review [12] does not focus on the manufacturing area of AR application, whereas the second one [13] does not deal with students from academia, but solely targets training operators in manufacturing. Another recent review from Eswaran and Bahubalendruni [14] reports the challenges and opportunities of AR/VR technologies for manufacturing systems in the context of industry 4.0; while the review is complementary to ours, it does not look at the technology readiness level of the implemented systems or the experimental strategies that are among our focuses.

The remaining literature on this topic is fragmented and most of the studies focus on a fraction of the topic; an account of the related works found in literature is presented here. Pellas et al. [15] analyzed how mixed reality (MR) can support education and the use of XR technologies with young students from primary and secondary school. They discuss the main uses for MR, the employed technologies, and the exploited research method designs, before highlighting the improvements and the difficulties that arise when utilizing MR in education. Maas and Hughes [16] focused on collecting information about how VR, AR, MR technologies contribute to the instruction of elementary, middle, or high school students, by providing attitude, motivation, engagement and delivering the learning outcomes and some competencies (critical thinking/communication/collaboration), that sometimes traditional education overlooks. Both papers focus on the K-12 range of years students and approach a broad array of fields where the XR spectrum might prove useful. Among other reviews, Guo et al. [17] studied the applications of virtual reality in maintenance but they did not cover the educational aspects of the XR technology; Wang et al. [18] focused their review on intelligent welding systems, including XR modalities, but they did not extend their work to the entire sphere of manufacturing systems.

The influence of AR technologies on higher education has already been extensively reviewed, comparing the effect of AR and non-AR approaches towards education whilst identifying major benefits and deficits of both methods, and creating a questionnaire evaluating the educational potential [19]. Kitchenham (2004) expanded those findings by exploiting a schematic review method; Bacca et al. [20] followed the PRISMA statement to report the findings, the advantages, and limitations of AR in education, and the purposes of using AR (explaining a topic, lab experiments, educational games among others). The review by Akçayır and Akçayır [21] focuses on the benefits and challenges posed by adopting AR for education. This approach supports learning by visualizing the tasks and provides an immersive experience, while at the same time having a mixed effect on the cognitive load of the students and showing usability problems and technology availability as major drawbacks. Technical problems are amongst the challenges highlighted by Sırakaya and Alsancak Sırakaya [22] when using AR in Science, Technology, Engineering and Mathematic (STEM) education; the main advantages are the contribution to the learner, the educational outcomes, and the interaction. Their research is limited to article journals indexed in the SSCI database, and therefore lacks depth of review.

Freina and Ott [23] examined VR in education, primarily for adult training or university students; they collected studies dating back only to the previous two years (2013–2014) and showed how most of those articles are in the medical field. The bias towards medical studies emerges also from Kavanagh et al. [24] that infer the domains for VR education from 379 scanned articles; the most frequent – excluding the health-related field – are engineering and science. Radianti et al. [25] described a total of 18 domains with VR supporting education, revealing that – out of a total of 42 entries – the most common is the engineering field. They also showed what types of technologies are employed in higher education, what the learning contents are, what learning theories are applied, and how the methods are evaluated.

One main topic of reviews in the field of VR for education are the so-called virtual reality laboratories. Ma and Nickerson [26] presented a debate over the value of hands-on laboratories against simulated and remote laboratories in the engineering field. The debate has extended over several years, thanks to the opportunity of creating better virtual reality plants that would open new possibilities of engineering education. Such technologies help motivating students and promoting distance learning [27]. During the last few years technological improvement and relative ease of use have shifted the debate towards the benefits of virtual labs, which are low-cost and low-maintenance good options as substitute of the real world [28]. VR labs will most probably be an established state of practice when it comes to lab education during and after the Covid-19 pandemic [29].

The same is true for student internships, that have been hindered by the spread of the virus: Handoko et al. [30] gathered descriptive research studies about mixed reality applications as a solution for students and graduates to be able to audit internships. Mixed Reality applications in education have also been collected to show how they are integrated into collaborative learning, teaching, and assessment activities, highlighting the importance of new technologies such as head-mounted displays (HoloLens, Oculus Rift and HTC Vive) [31].

Overall, comprehensive reviews over AR, VR and MR capabilities in the educational world are numerous, but they often refer to specific topics or purposes that are far from our specific manufacturing education objective. Examples of scopes for the reviews found in literature are cultural heritage [32], prediction of cybersickness [33], and immersive system research [34].

Many studies have been conducted on the use of XR spectrum technologies in education [13], however we feel that there is a need for a comprehensive review that would specifically target applications of those technologies in manufacturing teaching and training.

3. Research methodology

This systematic literature review follows as much as possible the guidance of a PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) statement [35] and its extension for scoping reviews [36]; however, the topic of this review is education in manufacturing with the aid of augmented, virtual or mixed reality technologies, which can be classified in a broad sense as a systematic review in engineering. We adopted the PRISMA protocol to guarantee a high standard quality for our review, however, since the PRISMA protocol was created for medical research, we discarded a few sections of the protocol that are not applicable to engineering reviews.

We selected the three most comprehensive research libraries for engineering applications containing literature articles on extended reality technologies and manufacturing engineering, with the ability to bulk export the results to a bibliography file, namely Web of Science (WoS), the ACM Digital Library (ACM), and IEEE Xplore (IEEE). We excluded other commonly used literature databases due to the lack of such exporting functionality, e.g., Google Scholar, that was fundamental to aggregate the results in a timely manner. Table 1 shows the definition of three functionally equivalent search queries over the corresponding three libraries. Moreover, we adopted slightly different queries to suit each research database, while also aiming at a homogeneous amount of search results from each search engine. Since even minimal query variations could yield hundreds to thousands of results, we selected those that produced a manageable number of articles for our review.

Moreover, we adopted slightly different queries to suit each research database, while also aiming at a homogeneous amount of search results from each search engine. The focus of the problem lies in the interpretation of acronyms. For example, VR can refer to Virtual Reality, but in some contexts, it may stand for Virtual Robot. Similarly, MR can signify Mixed Reality, but in other cases, it represents Maintenance Request

Table 1
Queries used for each research database.

Researcher	Source	Query string
R1	ACM	[[Publication Title: "virtual reality"] OR [Publication Title: "augmented reality"] OR [Publication Title: "mixed reality"] OR [Publication Title: vr] OR [Publication Title: ar] OR [Publication Title: xr]] AND [[Abstract: manufacturing] OR [Abstract: production]] AND [[All: education] OR [All: educational] OR [All: teaching] OR [All: learning] OR [All: pedagogic*] OR [All: didactic*] OR [All: "in the classroom"]] AND NOT [All: medical] AND NOT [All: surgery]
R2	WoS	((TI = (virtual reality) OR TI = (VR) OR TI = (augmented reality) OR TI = (AR) OR TI = (mixed reality) OR TI = (XR)) AND (TS = (educational) OR TS = (education) OR TS = (teaching) OR TS = (learning) OR TS = (pedagogics) OR TS = ("in the classroom")) AND (TS = (manufacturing) OR TS = (production))) NOT (TS = (medical) OR TS = (surgery))
R3	IEEE	((("All Metadata": "virtual reality" OR "All Metadata": "augmented reality" OR "All Metadata": "mixed reality" OR "All Metadata": "VR" OR "All Metadata": "AR" OR "All Metadata": "XR") AND ("All Metadata": "education" OR "All Metadata": "educational" OR "All Metadata": "didactic" OR "All Metadata": "pedagogical" OR "All Metadata": "learning" OR "All Metadata": "teaching" OR "All Metadata": "in the classroom")) AND ("All Metadata": "manufacturing" OR "All Metadata": "production"))

or Maintenance Ratio. This ambiguity can lead to an overwhelming number of irrelevant articles, requiring substantial time and effort to sift through.

Therefore, to strike a balance that allowed to retrieve a suitable volume of articles from each scientific database while ensuring they were relevant to our research topic, we tailored our queries slightly. This approach was particularly necessary because some databases contain more in-topic research and are naturally inclined to offer results that are relevant to our purpose. In contrast, other databases, being broader in scope and aiming at collecting numerous research from a variety of fields and areas, could potentially yield an immense number of manuscripts.

The execution of those queries produces an initial record of 621 journal articles and conference papers to review, corresponding to 249 results in WoS, 270 in ACM and 102 in IEEE. Fig. 2 shows a Sankey diagram with an overview of the review methodology process. The search queries, reported for each source database in Table 1, are based on a Boolean AND operation between three sets of keywords that are "education", "manufacturing" and "virtual/augmented/mixed reality" (see Fig. 3) and a NOT operation with an exclusion set of terms such as "medical" or "surgery" to exclude the majority of non-relevant results to manufacturing. Each of these sets contains the most common synonymous keywords. Namely, the education set is composed of the keywords educational, education, teaching, learning, pedagogics, "in the classroom"; the manufacturing set is composed of the keywords manufacturing, production; the "virtual/augmented/mixed reality" set is composed of the keywords virtual reality, augmented reality, mixed reality, VR, AR, XR. The exclusion set is medical, surgery. If the search engine allows it, the results are restricted to those in English language.

It is worth noting that the query for IEEE database does not include the exclusion set, because no articles containing the keywords medical, surgery are retrieved when using the query of Table 1.

As a second step, we used Rayyan [37], an online tool to aid systematic literature reviews. We imported in Rayyan the results from the three queries, thus forming the initial list of articles to review. The tool automatically removed the 53 duplicates found in the list of imported articles (see Fig. 2, operation 3). In a first selection round by abstract (see Fig. 2, operation 4), researcher R1 scanned all the 568 obtained records from their abstracts. During this phase, the objective was to manually exclude articles that did not align with at least one of the three primary categories education, manufacturing, and "virtual/augmented/mixed reality," as illustrated in Fig. 3. This operation allowed excluding the majority of false positives that had arisen from the automatic keywords search results. For example, articles related to virtual reality movie production for educational purposes fell into the category of false positives. To ease the process, Rayyan allows reviewers to designate each article as "included" or "excluded" from the review. Additionally, the reviewers can mark an article as a "maybe" and postpone the decision. In this phase, R1 marked as a "maybe" any articles that could not be accepted or rejected from only reading the abstract. The articles in "maybe" were considered as temporarily accepted.

Table 2
Values for the calculation of the sample size.

Symbol	Name	Value
N	Population size (number of articles)	568
$(1-\alpha)$	Confidence level	95%
Z	Critical value	1.96
e	Margin of error	10%
p	Likely sample proportion	50%
n	**Sample size (number of articles)**	**82**

In our methodology, we opted not to rely on rigid, predefined definitions of terms such as [VR, AR, XR], manufacturing, or education as the sole criteria for article selection. Instead, we employed a more flexible approach, considering the presence of any of the three keywords – [VR, AR, XR], manufacturing, and education – as an indicative factor for further exploration and reporting on an article's content. This approach enabled us to include a broader range of articles, covering various topics. For instance, our selection included articles related to topics as varied as leather manufacturing, specific manufacturing processes (e.g., welding), elementary school education with ties to the manufacturing industry, or training programs for industrial operators (a form of education).

To validate the reliability of R1 decisions, researcher R2 – blinded from the previous selection – did the same operation in Rayyan. However, instead of scanning the entire list of articles again, R2 scanned only a randomly selected representative sample size of the population, namely 82 papers (this is represented in Fig. 2, operation 4). Note that Rayyan also provides a blinded review method for each author to make their independent decisions. Parameters such as the percentage of agreement among researchers, or the Cohen's score, can help define the minimum significant number of articles to rescan [38]. A standard procedure [39], using Cochran equation [40] produces the results presented in Table 2, where n is the sample size, Z is the critical value of the Normal distribution at $\alpha/2$ (where $\alpha = 0.05$ for a confidence level of 95%, and the critical value is 1.96), e is the margin of error or confidence interval, p is the estimated sample proportion, and $q = (1-p)$. A finite population correction is applied [39], where N is the population size. The minimum number of articles that R2 needs to check is 82.

The 95% confidence level is a very common choice for any standard application, and the margin of error is set to 10% because it is half the extension of the ranges in which the k score could fall (see Table 3). The value of p should be set based on what the expected agreement result is. In this case the result was unknown and, in order to be the most conservative possible, we selected a value of 50%.

Then, to estimate the Inter-Rater Reliability of this selection, the percentage agreement α and Cohen's k [41] were calculated on the sample of 82 papers [42], and the scores are shown in Table 4.

To evaluate the strength of agreement associated with the k score, the values of Table 4 were compared to the ranges of k [43]. Since the obtained score positioned the agreement level between researchers

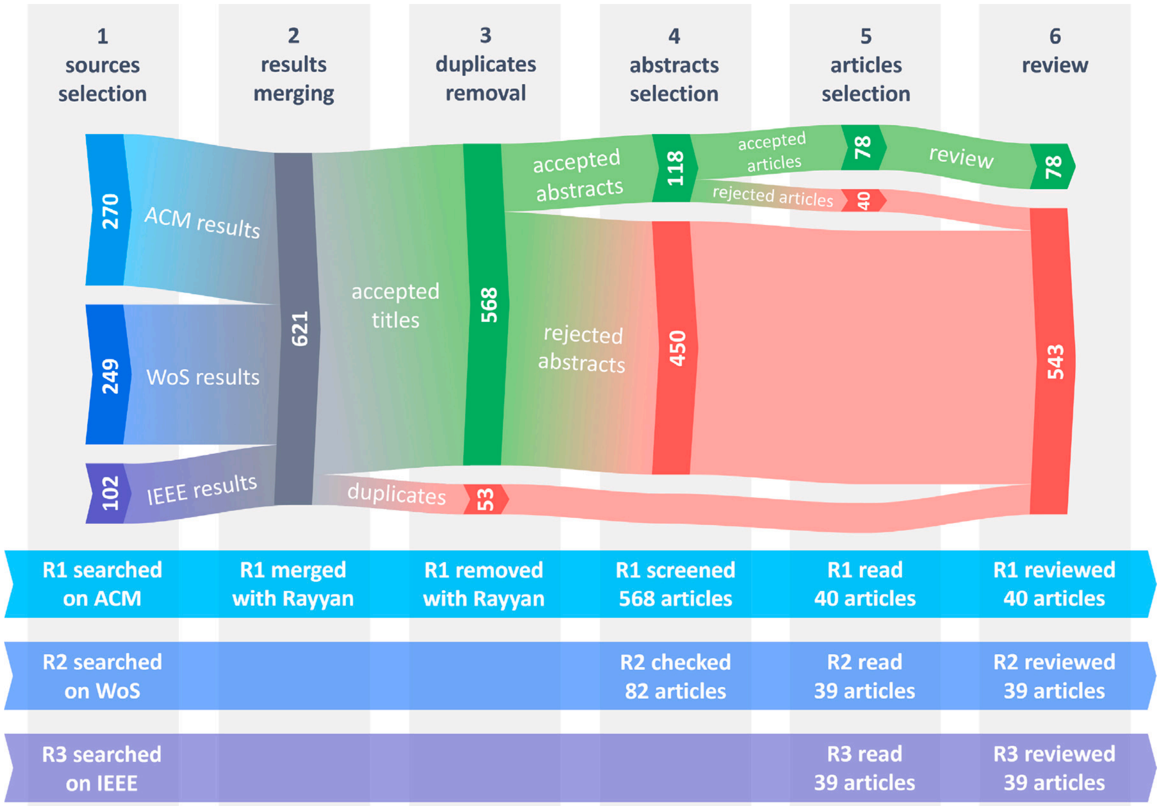

Fig. 2. Sankey diagram of the article selection process and researchers' tasks.

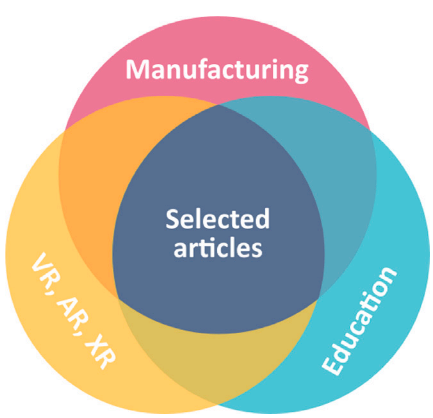

Fig. 3. Venn diagram for the search query. Only the articles that match all of the three categories "Manufacturing", "VR, AR, XR" and "Education" are selected for the literature review.

Table 3
Strength of agreement ranges for k score.

Range of k	Strength of agreement
<0.00	Poor
0.00–0.20	Slight
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
0.81–1.00	Almost perfect

in the almost perfect range of strength of agreement, it was safe to assume that the labels assigned by the first researcher, to the entire articles database, were representative of the decisions that all the researchers would have made; thus, the decisions of the first researcher

Table 4
Values for the calculation of percentage agreement, α, and Cohen's k score.

Name	Value
Total number of papers	82
Rater agreement	75
Rater disagreement	7
Percentage agreement α	**91.46%**
Cohen's k	**81.30%**

are representative for the inclusion (118) or exclusion (450) of the articles in the abstracts review, as shown in Fig. 2, operation 4. In operation 5, researchers R1, R2, R3 used the batch of accepted articles from the abstracts selection to populate a result table based on the taxonomy showed in Table 5. Each researcher was allowed to annotate other unforeseen and interesting aspects of a certain article in a specific column named "other relevant findings". Thus, the researchers read the articles and, either populated the table, or excluded each article not fitting the scope of the review (see Fig. 3). The criterion for article selection was that if the responsible reviewer included the article, this was to be considered accepted in the final list. This paper consists of a final review that includes 78 articles and excludes 40 (see Fig. 2, operation 6). In total, from the original 621 article, 543 were excluded during the review process and 78 articles were included in the final review.

The following step was a semantic analysis of the papers, aimed at establishing the kind of data that could be robustly extracted from this sample of the literature. While quantitative data about the nature and dimensions of the different studies were often missing or not homogeneously presented, it was possible to extract qualitative information-rich data about, among other things, applications and tools. Among the various elements of the taxonomy, the different experimental strategies deployed were also collected, as well as the TRL of the examined solutions, for which a value from 0 to 9 was assigned

Table 5
Taxonomy for the extraction of information from retrieved articles.

Category	Header	Description
Paper information	Title	Title of the article
	Year	Year of publication
	Authors	Authors' names
	Country	Country of affiliation of the first author
	Venue	Venue of the publication
	Journal	Name of the publication
Criteria	AR	Is the article focused on AR?
	VR	Is the article focused on VR?
	XR	Is the article focused on XR?
	Manufacturing	Does the article focus on manufacturing?
	Education	Does the article focus on education?
Objective	Application	The application for which the study was developed
	Study goal	The final goal of the study
Technology	Hardware	The hardware used to deploy the XR technology
	Software	The software used to deploy the XR technology
Experimental strategy		The experimental strategy used for the application (refer to Section 4.3)
Quantitative evaluation	Measurements	Measured parameters for evaluation (e.g., time to complete and error rate)
	Learning curves	Does the study report learning curves?
	Experimental strategy	The experimental strategy used for the application (refer to Section Experimental strategies)
Qualitative evaluation	Questionnaire	The kind of questionnaire used in the experiment
	Scale	The scale used in the questionnaire (e.g., Likert) and the levels
	Demographics	Population The number of participants
	Expertise	The participants' level of expertise
	Gender distribution	The distribution of gender in the experiment's population
TRL evaluation	TRL	The Technology Readiness Level score

according to the NASA TRL system — first codified by John Mankins [44]. TRL is an ever-evolving rating scale to assess the maturity level of a particular technology project. Other variations of the scale are available, and many organizations adopted their own, e.g., even compressing the framework levels down to three [45]. However, for this review, we kept Mankins' TRL scale. Each reviewer followed the methodology that we established in this section. The complete taxonomy of the collected data is presented in Table 5.

The results of this review are grouped and reported by means of thematic analysis (TA) and quantitative analysis. TA is a common form of analysis for qualitative research: it allows for identification of patterns and clusterization of themes in qualitative data, and it offers an alternative to discourse analysis [46]. TA can be used to address most types of research questions, and its peculiarity is the capability of analyzing most kinds of qualitative data and it is not limited to large data sets only [47]. A sound approach to the application of TA is widely available and exploited by this research [48].

4. Results

In total, we analyzed 78 articles (see Fig. 4a): 47 (57%) articles were about VR applications, 30 (36%) pertained AR, and the remaining 6 (7%) were labeled as XR, meaning that their main topic was an application of both AR and VR in a mixed or extended form (the total number of mentions does not match the number of papers, because some of them applied more than one technology during the study).

The majority of the analyzed studies (69%) were published in conference proceedings, while the rest (31%) reached the audience through publication in journals (Fig. 4b).

No journal in particular stood above the others for number of published articles, though we should mention Computers in Industry, which published three articles, more than any other. Table 6 shows journals and conference proceedings with more than one publication (journals with only one are not included in the table).

Only two researchers published more than two articles on the topic, namely Michael Hamilton and Junfeng Ma. Fig. 5 shows other authors that appear more than one time in the list of authors. A total of 307 authors contributed to the publication of the 78 collected articles.

The majority of studies was published in 2019 and 2020 — since this review stops at the beginning of 2021, works that have been published afterwards do not appear.

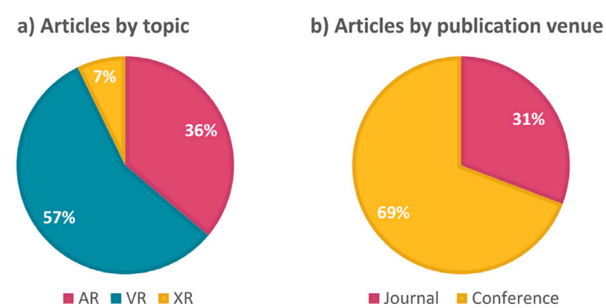

Fig. 4. (a) Articles by topic. (b) Articles by publication venue.

Analyzing the trend of publications about AR in education by year, Bacca et al. [20] said: "One of the issues that emerges [...] is that more research needs to be undertaken in the topic of AR in education". Such trend is similar for XR technologies as presented in Fig. 6. In recent years, the number of studies on the topic has actually increased. The last five to six years saw a growing trend, thus highlighting once more the need for an updated review of studies focused on education with XR technologies.

Fig. 7 shows the Nations that contributed the most to the review topic, which are United States and Germany, while also United Kingdom, China, Poland and México played an important role. To build the map of publications per Nation, we used the first author's country of affiliation for each paper.

4.1. Applications and goals

In this section, we report the main applications and goals driving the education in manufacturing with XR.

4.1.1. Applications

The list of papers we analyzed presented a fragmented and diverse number of XR technologies applications. It would not add much value to list every specific one, so we applied the TA approach to find some common patterns. We selected three major sets to describe the applications (educational activity, application domain, and specific application) and assigned the papers to one or more categories in

Table 6
Journals and conference proceedings with the highest number of publications.

Venue	Name	Number of articles
Journal	Computers in Industry	3
Journal	Computer Applications in Engineering Education; Interactive Learning Environments; Journal of Mechanical Design; Sustainability; IEEE Access	2
Conference	Procedia Computer Science 75; Proceedings of the 14th International Conference on Mobile and Ubiquitous Multimedia; Proceedings of the 12th ACM International Conference on Pervasive Technologies Related to Assistive Environments; 2020 6th International Conference of the Immersive Learning Research Network; IFIP International Conference on Advances in Production Management Systems	2

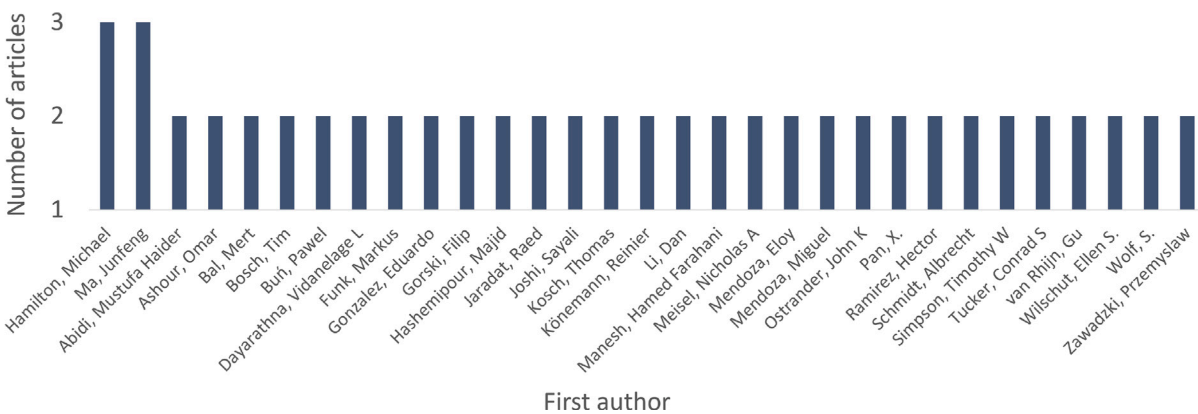

Fig. 5. Number of articles published by author. Only the authors with at least two entries are visualized.

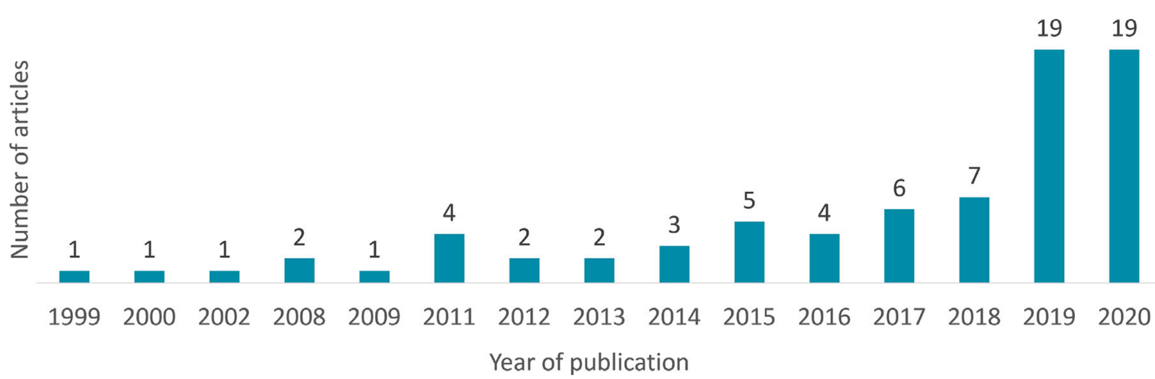

Fig. 6. Number of reviewed XR articles published by year.

each of them. All the results obtained from the extrapolation of the main applications of XR in education in the field of manufacturing are summarized in Fig. 8. Note that each article might belong to multiple sets and the sum of articles per set does not match the total number of articles in the analysis.

Educational activity. This set contains the two main forms of education for manufacturing: training (39 articles) for workers in the manufacturing field that are already skilled in some activity, and teaching (39 articles) for students of any age and background, when the research was performed in a laboratory or in a classroom, or as part of any academic activity.

Application domain. This set has four categories: assembly (32 articles) contains every activity where a XR technology was used in an assembly process; manufacturing (25 articles) comprises all the activities involved in the actual manufacturing of a part, from the more advanced like additive manufacturing, to casting, welding and any material removal technique; the design category (16 articles) involves all the activities such as parts design, mold design, PLC circuit board design and also design of the phases of production; system configuration (9 articles) refers to the manufacturing system as a whole, so any activity that affects it. In the application domain set, most of the studies used the assembly phase of production to perform their research, but also manufacturing activities where often utilized. The design phase and system configuration where seldomly explored for the use of XR technologies; still, design processes have an edge over system configuration and were used nearly twice as much.

Specific application. This set describes the individual applications involved in the XR experiment. Among those we categorized: lab activities (5 articles), additive manufacturing (4 articles), PLC programming (3 articles), maintenance (3 articles), quality (3 articles), safety (3 articles), lean manufacturing (2 articles), casting (2 articles), measurement (2 articles), and welding (2 articles). Specific applications mentioned in the reviewed articles are numerous, and the spectrum of topics is broad: there is no predominant application. The slightly most cited category – laboratory activities – regards any experimental setup that involves XR technology use in a laboratory environment.

It is worth noting that the three sets are hierarchical (see Fig. 8) and, apart for the two categories in the set educational activity, all the other categories are also non-exclusive, i.e., each paper can belong to only one of the two educational activity categories, but it can fall in multiple categories in both the application domain and the specific application sets.

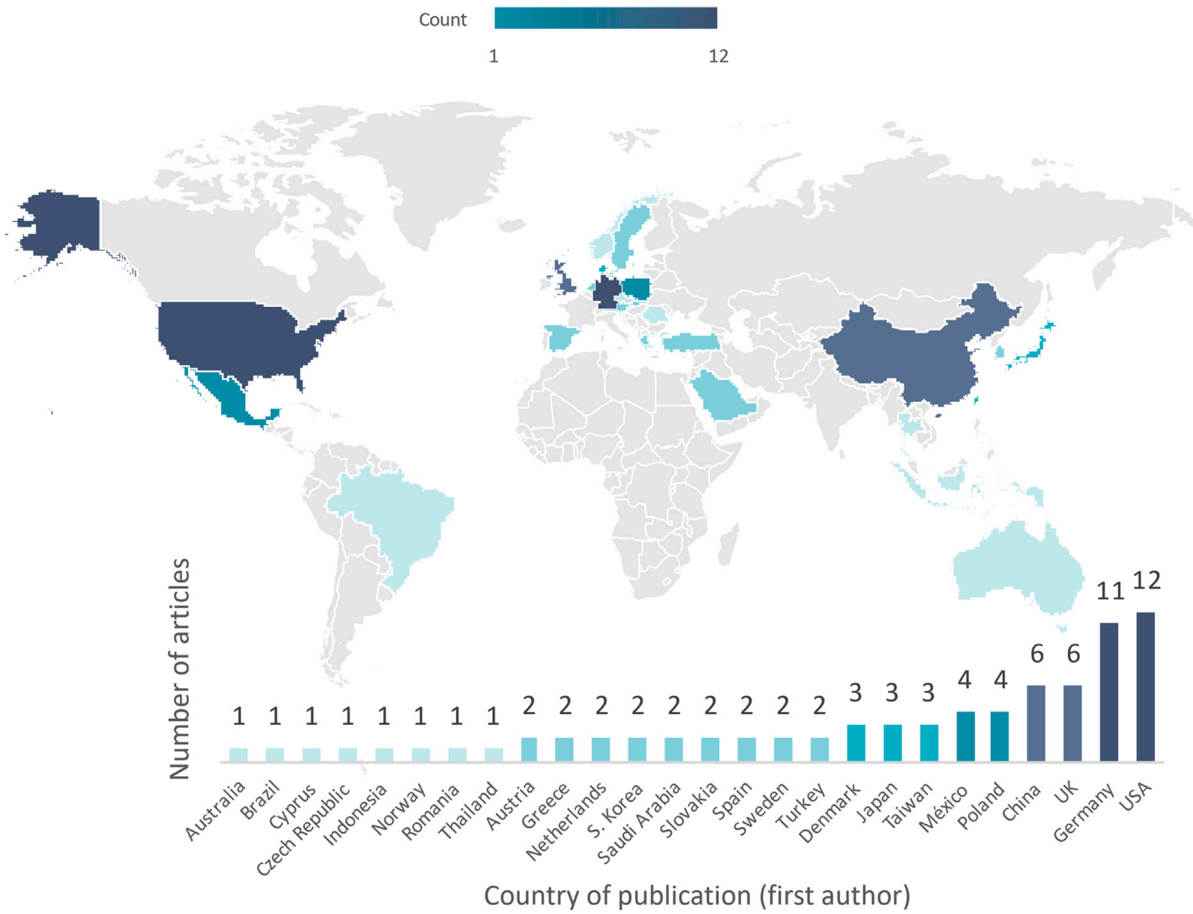

Fig. 7. Number of articles published by country (country of affiliation of the first author).

4.1.2. Goals

Thematic analysis is also applied to the goals that each reviewed paper wanted to achieve. We selected six main application goal categories (see Fig. 9) where the article might fall. It is worth noting that a paper might be added to more than one category at each time. The following paragraphs explain the meaning of the categories' names that are summarized in Fig. 9.

Transfer knowledge (61 occurrences). The most common goal, which includes both creating a better training environment for workers and developing an improved learning experience for students in the context of lectures or laboratories. For example, process times for production tasks can be shortened with virtual training, and error rates reduced [49,50]; on the other hand, educational applications simulate the cooperation between industrial robotic manipulators and humans, to enhance the learning process [51].

Enhance skills (14 occurrences). The second goal, which implies the use of XR to help employees complete their jobs in an easier way, e.g., helping a technician in dimensional validation of a part [52], or assisting designers in planning the correct assembly sequence of components [53].

Reducing time or cost (21 occurrences). The objective of an article in this category is to reduce the impact of a virtualizable application in terms of time or cost. It is a goal that appears quite frequently in the manufacturing domain, as much as in more than 25% of the reviewed articles. Examples of such kind of research are providing virtual assembly training to employees before deploying them on the production line [54], and fixing mistakes in the virtual environment before real production in the additive manufacturing field [55].

Stimulate interest (11 occurrences). This category comprises of the studies that use virtual technologies to spark curiosity in young students or workers who are exposed to the manufacturing activities with an innovative approach. The objective of research under this category is to attract young talent to manufacturing [56], or to accentuate students' enthusiasm for practice and innovation [57].

Improve safety (6 occurrences). Some applications are intrinsically dangerous to men or machines, so research tries to virtualize production processes to reduce risks and avoid hazards. This goal is attributed, for example, to research making use of XR technologies to avoid exposing workers to hazards [58], or supplementing teaching with virtual machines, thus avoiding the risks associated with the use of dangerous equipment for both students (health risk) and the machines (breaking risk) [59].

Bridge study to work gap (6 occurrences). This goal pertains research focused on bridging the existing gap between education and on-the-field work [60,61]. It is important for future engineers to have as many experiences as close as possible to real production tasks as possible to fully understand what they are taught.

4.2. Development tools

In this section, we have reported the main development tools used in the reviewed articles, namely the preferred software and hardware.

4.2.1. Software

If we look at the software mentioned in each article of this review, it is possible to categorize it as parts of an interactive XR visualization pipeline (see Fig. 10). Firstly, a real or fantasy world environment and all its objects have to be created with the aid of modeling software. Secondly, all the objects and, eventually, the virtual world scenario, have to be registered in the real world. Thirdly, the rendering of the

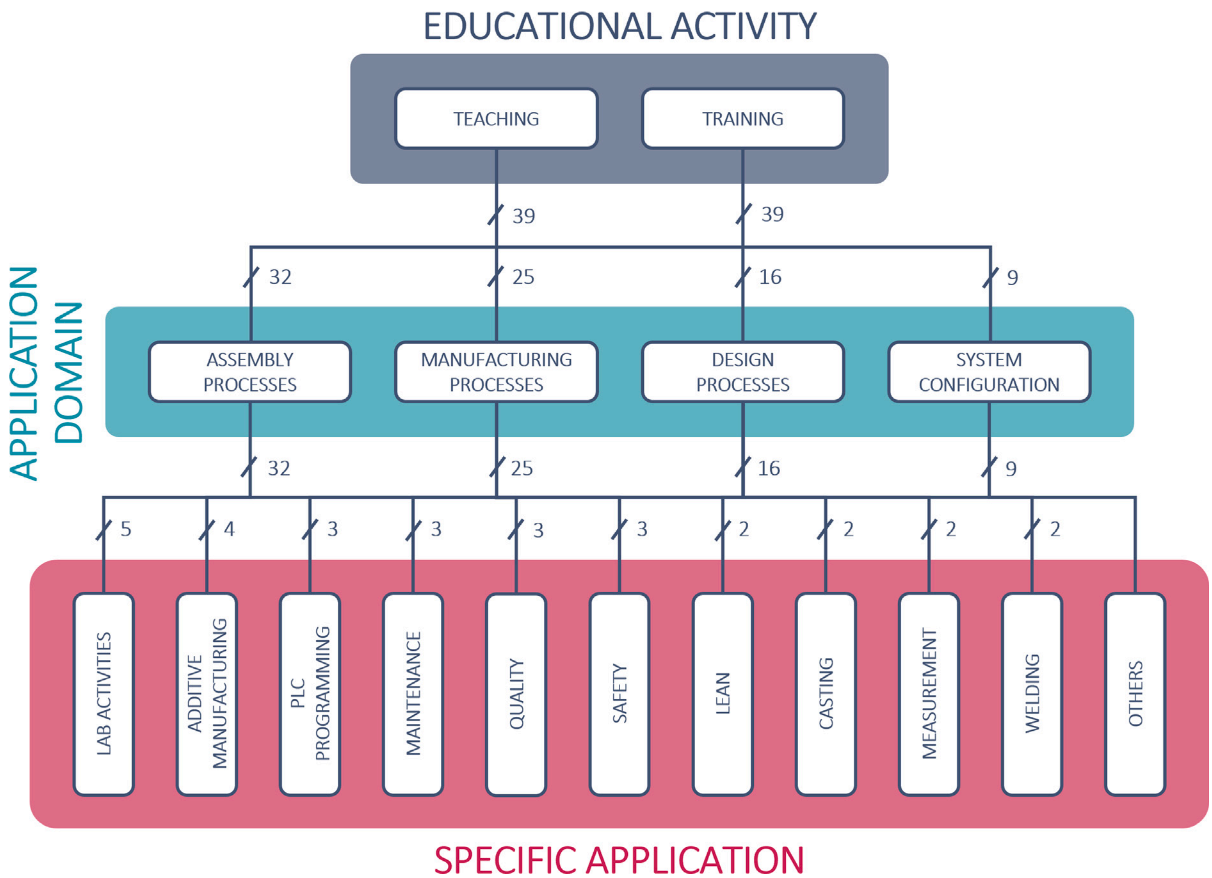

Fig. 8. Taxonomy (sets and categories) for the applications presented in the retrieved articles. The numbers indicate the amount of articles categorized. Note that an article can belong to multiple categories.

Fig. 9. Graphical summary of the identified main application goals for the reviewed papers. The number of articles for each application goal category is indicated on each branch.

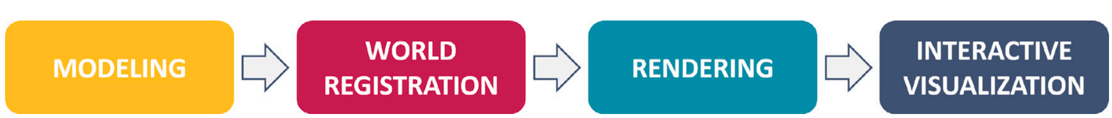

Fig. 10. Stages of an interactive XR visualization pipeline.

XR experience can be generated with ad hoc software. Finally, the interactive visualization can take place through the use of dedicated software to play the interactive XR scenario. Each of these specific software solutions is presented in the following subsections.

Modeling. The manufacturing processes and 3D objects used in each reviewed article are mostly modeled with two different categories of software: manufacturing-specific computer-aided design (CAD) and generic graphical modeling software. Examples of the first category are Siemens NX (mentioned twice), an advanced high-end CAD, computer-aided design (CAM) and computer-aided engineering (CAE) software for engineering applications, Dassault Systèmes Digital Enterprise Lean Manufacturing Interactive Application (DELMIA) (mentioned twice), a global industrial operations software that specializes in digital manufacturing and manufacturing simulation, Catia (mentioned once) that is a multi-platform software suite for CAD, CAM, CAE, 3D modeling and product lifecycle management, VRED (mentioned once) that is a 3D visualization software for automotive designers and automotive engineers, Autodesk Revit (mentioned once) that is a building information modeling software for architects, landscape architects, structural engineers, mechanical, electrical, and plumbing engineers, designers and contractors, and Creo (mentioned once) that is a family of CAD apps supporting product design for discrete manufacturers. Examples of the second category of software are 3DS Max (mentioned six times) that is a professional 3D computer graphics program, Autodesk Maya (mentioned three times) that is a 3D computer graphics application, Solidworks 3D (mentioned three times) that is a CAD program, Blender (mentioned twice) that is a free and open-source 3D computer graphics software, Rhinoceros (mentioned once) that is a commercial 3D computer graphics and CAD application software and OpenSCAD (mentioned once) that is a free software application for creating solid 3D CAD objects.

World registration. World registration is the operation of finding the 3D coordinates and orientation of the real camera with respect to the real world and using those coordinates located the virtual camera in the same position and orientation. The objective is to align the virtual with the real views to provide users with a coherent first-person perspective of the mixed environment and, thus, the illusion of immersion. In XR applications, there is a distinction between AR registration, aimed at localizing the device's camera and the AR objects in front of the user in the real world, and VR registration, aimed at localizing the eyes of the user, with respect to the virtual world. In all cases, without a correct world registration the interactivity of the XR experience is missing or easily lost. Among the negative effects of a bad registrations there are: drifting, when the camera moves away, and jittering, when the camera moves back and forth. In both cases, immersion is broken because users reject what they see or may even become "cyber-sick", i.e., nauseous.

Common software solutions for registration in AR are libraries such as ARkit and ARCore, respectively from Apple and Google. The registration is done through computer vision algorithms. Typically, the method involves a monoscopic camera. In VR, each hardware vendor typically has an in-house solution that includes hardware and software methods. A typical registration can be done with projector camera pairs or depth sensors, e.g., the Microsoft Kinect or, more recently, the Intel Realsense camera that includes both. These methods consist in projecting an infrared matrix onto the real world and measuring the deformations of the matrix through the infrared camera. The geometry of the world is inferred through this reverse engineering method. One of the most used algorithms is RANSAC, the random sample consensus [62] that records a sequence of images across time and looks for features in the world by comparing frames; when a critical mass of points is reached, it generates a 3D structure of the world.

Rendering and interactive visualization. Nowadays, the rendering and the interactive visualizations of an XR experience rely mostly on game engines. Even if this might sound surprising in manufacturing or engineering applications, it is the gaming industry that paved the way through its financing and innovation advancements to many of the computer science technologies we currently use. For example, the game industry has pushed hardware and software graphics visualization with graphics processing units (GPUs), up to the point that today's supercomputers have GPUs, rather than central processing units (CPUs), to perform faster computations. It is natural that the best rendering and interactive visualization software is found in terms of game engines, up to the point that almost all the articles in this review rely on them for rendering and visualization. In particular, 29 articles prefer and mention Unity, for its quickness and easiness of use, while only one of the articles prefers and mentions Unreal, an alternative to Unity that is more complicated to learn, even if it leads to cinema-quality photorealism, and the rest of the articles found different solutions, such as A-Frame (mentioned once) that is an open-source web framework for building virtual reality (VR) experiences, CoherentUI (mentioned once) that is a graphical user interface system specially designed for games, or even own developed software (mentioned twice) or Android apps (mentioned once).

4.2.2. Hardware

Research in the AR domain is mainly based on 2D projection, head-mounted displays (HDMs) in the form of glasses, or tablet/smartphone devices. In the VR domain, research is based on stereo projection, CAVE projections, 3D visualization devices, or immersive HMDs. In the XR domain, it is normally performed without ad hoc hardware for it. If any hardware is used, it is mainly VR or AR hardware that is applied in hybrid forms or in connection with other methods to create XR experiences. For example, the hardware for an XR application can consist of traditional AR/VR devices, complemented with other kinds of hardware, such as haptic devices or additional sensors, in order to expand the capabilities of the commercial hardware and fulfill the application requirements. Among the 78 reviewed articles – considering that one article might adopt more than one device – the most adopted hardware is an immersive HMD (26 occurrences), followed by any forms of glasses (14 occurrences) including AR glasses, shutter glasses (often in conjunction with 3D projectors or 3D displays), and mono-eye goggles. The articles also present PC-based applications (13 occurrences), i.e., considering the 3D representations of the world behind a display as VR, which can be considered a non-immersive type of VR. Less used but not unpopular, all the AR experiences that make use of tablets (11 occurrences) or smartphones (3 occurrences) for their displays and opposed cameras that can mask the real world and show an augmented version of it. Finally, it is important to mention how the old VR systems – consisting of projector-based (5 occurrences) or CAVE-based (4 occurrences) immersive systems – still occupy a consistent slice of the adopted technologies. Even if specific device models might become soon obsolete, at the time of this review, the most used HMDs are the HTC Vive (9 applications) and the Oculus Rift (9 applications), while the most used glasses are the Microsoft Hololens (6 applications, 4 with the first version and 2 with the second version). Lastly, it is quite rare but worth mentioning the development and adoption of customized solutions such as, for example, the HMD VRTEX 360 VR Welding Trainer used for welding applications (1 occurrence), instead of the customization of the widespread commercial devices presented above.

4.3. Experimental strategies

Developing new XR teaching systems requires to test their usability and teaching efficacy. Among the 78 reviewed articles, 43 (55%) perform experiments to validate one or two main aspects: the usability of the XR system and/or the ability to teach with the XR system. For these purposes, a variety of experimental strategies are applied. While we would have expected to find a large number of proper experimental designs, all that we found was very basic experimental strategies. In particular, we found that the authors mainly dealt with questionnaires and the timing to deliver them, or how to split the population in test and control groups. We have summarized in Fig. 11 the fourteen experimental strategies (A-N) found in 43 articles, namely an overview of the main scientific methods applied in several combinations. In Table 7 are reported the references to each article in this analysis and the exact articles count used for Fig. 11.

4.3.1. Comparison of the reviewed experimental strategies

Among the 43 articles performing experiments, the most common experimental strategies A (19%) and B (14%) mainly aim at testing the XR system for its usability. In both these strategies, firstly, the XR system is tested by a group of users, then they are asked to fill in a post questionnaire. The main difference between strategies A and B is that in A the performance of the users on XR system is recorded. What is recorded during the performance depends on the type of XR task performed and we have analyzed it further in subsection Analysis of the measurement methods. The ability to teach is in a few cases verified with post questionnaires that focus on the learning outcomes of the users. Most post questionnaires are focused on the usability of

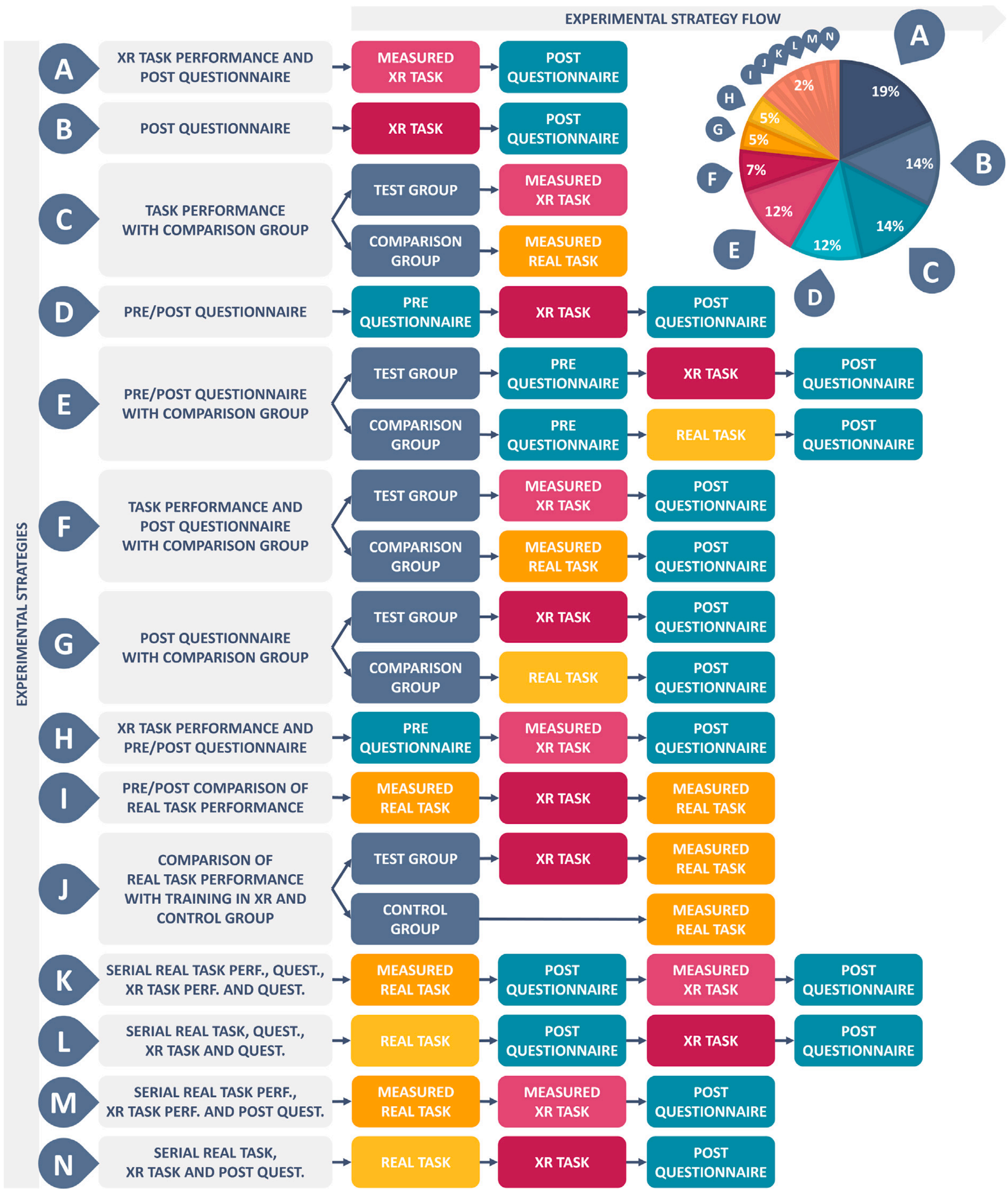

Fig. 11. List of experimental strategies. The pie chart shows the distribution of strategies among the 43 articles that perform experiments.

the XR system; in particular, the articles use standard questionnaires such as the NASA-TLX [128], the system usability scale (SUS) [129], the simulation sickness questionnaire (SSQ) [130], and the presence questionnaire (PQ) [131], or customized questionnaires. See subsection Analysis of the questionnaire methods for further details. Strategy C (14%) introduces another scientific method that is quite effective: the use of a comparison group. The users are split into two groups. One group uses the XR system, for example, the users are aided by AR on the real task, and the other group performs just the real tasks, without any XR. This technique allows to compare the users' performance on the task at hand, with and without the XR system. It can be used to verify both the usability and the teaching efficacy of the XR system. Strategy F (7%) is similar to C, but it also requires the users of both test and comparison groups to fill in a post questionnaire after that they have completed the measured task. Strategy G (5%) is similar to F, but it does not measure the XR and real task performances: all the evaluations and comparisons are done solely with the post questionnaires. Strategy D (12%) introduces another technique: the pre and post questionnaire. Firstly, the users are tested on their knowledge with a pre questionnaire. Then, they execute the XR task. At the end, they are asked to fill in a post questionnaire. The technique allows to evaluate the learning outcome from the XR task. It also allows to evaluate the usability of the XR system by asking ad hoc questions in the post questionnaire. Strategy E (12%), equally preferred as strategy D, it is

Table 7
Experimental strategies by number of articles.

Strategy	Strategy description [articles]	N. of articles
A	XR task performance and post questionnaire [63–70]	8 (19%)
B	Post questionnaire [51,71–75]	6 (14%)
C	Task performance with comparison group [50,52,76–79]	6 (14%)
D	Pre/post questionnaire [56,80–83]	5 (12%)
E	Pre/post questionnaire with comparison group [58,61,84–86]	5 (12%)
F	Task performance and post questionnaire with comparison group [87–89]	3 (7%)
G	Post questionnaire with comparison group [90,91]	2 (5%)
H	XR task performance and pre/post questionnaire [92,93]	2 (5%)
I	Pre/post comparison of real task performance [54]	1 (2%)
J	Comparison of real task performance with training in XR and control group [94]	1 (2%)
K	Serial real task performance, questionnaire, XR task performance and questionnaire [95]	1 (2%)
L	Serial real task, questionnaire, XR task and questionnaire [96]	1 (2%)
M	Serial real task performance, XR task performance and post questionnaire [53]	1 (2%)
N	Serial real task, XR task and post questionnaire [97]	1 (2%)
Total		**43 (100%)**
No strategy	No experiments [49,55,57,59,60,98–127]	35 articles

very similar to it, with the difference that the users are also split in – at least – two groups and a comparison from pre/post questionnaires is made also on the learning outcomes from the XR task and the real task (without XR system). Note that strategy D does not measure the performance on the XR task. This operation is done by strategy H (5%), as an improvement of strategy D. In strategy H, a pre questionnaire is followed by the measured XR task and this latter is followed by a post questionnaire. We noted that there are no articles that have used an experimental strategy that merges the characteristics of strategies D, E and H: pre/post questionnaires, test and control groups, and measured performance on the tasks. Strategies I to *N* (each used once) are worth reporting because among those there are examples of how not to properly test an XR system (refer to Fig. 11. List of experimental strategies. The pie chart shows the distribution of strategies among the 43 articles that perform experiments. for each strategy). In strategy I, firstly, the performance of a user is measured on a real task; secondly, the training is moved to the XR task; finally, the user performance is measured again on the real task. This experimental strategy allows to overcome the limitations of not being able to measure the performance directly on the XR task; however, it comes with a pitfall: testing the second performance on the real task could present an improvement that is due to having performed the real task once before the XR training and not to the XR training itself. In strategy J, the same problem addressed in strategy I (not being able to directly measure the XR task performance) is solved by measuring the performance on the real task that is executed either after the XR task (test group) or directly (control group) by to separated groups of users. This experimental strategy is quite indirect, as the results concern only the performance on the real task and do not provide any insights on the usability of the XR system. In strategy K, the user executes the measured real task, fills in a post questionnaire, then executes the measured XR task and fills in another post questionnaire, the performance is recorded on both tasks. Strategy L is similar to K, but the performance on the real and XR tasks is not recorded. Both strategies K and L have similar pitfalls: the second task (XR) is affected by the experience on the first task (real). Thus, these experimental strategies are to be preferred only if it is not possible to ask the users to execute the XR task without having experienced firstly the real task. Otherwise, splitting the groups and executing either the XR or real task (strategy F instead of K, and strategy G instead of L) is preferable to further separate the outcomes. In strategy M, the measured real task is followed by the measured XR task and then by a post questionnaire on both. In strategy N, the real task is followed by the XR task and then by a post questionnaire on both; in this case, differently than in strategy M, the task performance is not measured. Strategies M and N are similar to strategies K and L if the first post questionnaire is removed, thus they suffer from the same pitfall: the second task (XR) is affected by the experience on the first task (real).

4.3.2. Analysis of the qualitative evaluation methods

Among the 43 articles performing experiments, only 8 articles applying strategies C (6 articles), I (1 article) and J (1 article) do not make use of a questionnaire (qualitative evaluation method), whereas the other 35 articles make use of one or several standard or customized questionnaires. Of all the customized questionnaires adopted by 25 articles, 14 use at least a 5-item Likert scale [132], which allows to further characterize the strength of a participant's answer, other than its direction (positive or negative answer). It is also common to have a few open answers to collect wider feedback. On the other hand, the standard questionnaires applied in the experimental strategies can be easily listed here: the most used questionnaire (12 articles) is the NASA task load index (NASA-TLX) proposed by Hart and Staveland [128]. Other questionnaires are the system usability scale (SUS) [129] used in 7 articles, the simulation sickness questionnaire (SSQ) [130] used in 3 articles, and the presence questionnaire (PQ) [131] also used in 3 articles. One article uses the cube comparison test (CCT) [133] to analyze the user spatial abilities.

4.3.3. Analysis of the quantitative evaluation methods

Among the analyzed articles, twenty-two of them adopt direct measurements (quantitative evaluation methods). The most common measured parameters are the task completion time (TCT) (21 articles), the number of task errors (9 articles), the number of aid requests (3 articles), the amount of spatial displacement (2 articles) in the execution of a task (e.g. the welding quality depends on keeping the tool at a precise distance from the welded parts), and the number of trials needed to successfully complete a task for the first time over few repetitions (2 articles). Overall, TCT is the simplest parameter to measure, although it is important to correctly define when a task begins and ends to keep the measurement consistent throughout the experiments. The number – and types – of task errors highly depend on the specific task. For example, in assembly applications (14 articles), it is possible to measure: the number of infeasible assembly operations, the number of excessive reorientations, the number of difficult assembly operations, the number of non-similar (dissimilar) assembly operations for parts of similar function, the number of unstable assembly operations, etc. Thus, it is important to define all the measurable errors prior to the execution of the experiments. The aid request is relative to the use of the XR devices, as much as the inability to proceed through the task at hand. Finally, the number of trials needed to succeed is an interesting parameter that helps to create a comparable baseline for several operators when the experiment addresses the operator's ability to execute the task with or without an XR device, rather than the ability to complete the specific task. The number of trials is related to the concept of learning curve analyzed in the next subsection.

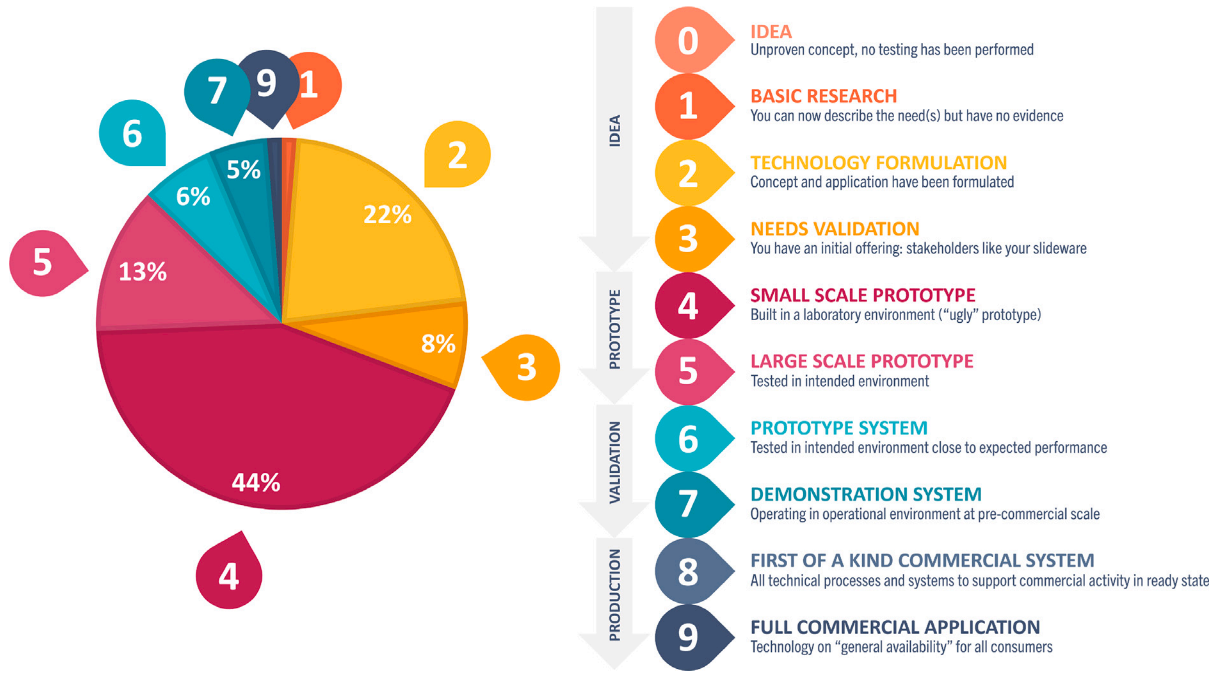

Fig. 12. Technology readiness level (TRL) analysis of the reviewed articles.

4.3.4. Learning curves

Three out of the twenty-two articles specifically measure a parameter in relation to several repetitions of a task, presenting what is called a learning curve [134,135] over that parameter. In particular, Liang et al. [78] measure the welding spatial displacements over repeated tasks, Hovrejvsi et al. [77] and Wilschut et al. [89] measure the completion time over assembly repetitions.

4.3.5. Demographic analysis

Among the 43 articles performing experiments, only 20 disclose the gender balance of the participants. We have also decided to not report any statistics about it. More relevant seems to be the source of the participants that is mentioned in 40 articles, and we have classified in four categories: unspecialized students (16 experiments), specialized students (15 experiments), untrained operator (9 experiments) and trained operator (8 experiments). Note that some of the experiments use more than one category of participants, thus the sum of the items in the four categories is greater than the number of experiments.

4.4. Technology readiness level

The technology readiness level (TRL) analysis of the articles (see Fig. 12) reveals a typical normal distribution over the TRL scale, with a peak of applications on TRL 4 (44%), which means that a small-scale prototype has been developed in laboratory and not properly tested. The second largest groups are TRL 2 (22%) and TRL 3 (8%) that represent, together, 30% of the articles in which an idea is formulated (TRL 2) and the design is presented (TRL 3) but it lacks even a small-scale prototype. The third largest group is TRL 5 (13%) that is composed of the articles that have a prototype deployed in the intended environment and start testing it. The next groups to follow are TRL 6 (6%) and TRL 7 (5%) that represent, together, 11% of the articles in which the prototype is running in the intended environment, close to expected performance (TRL 6), and even ready to be commercialized (TRL 7). There are almost no articles for TRL 1 and TRL 9, and no articles at all for TRL 0 and TRL 8. This is expected because at the extremes of the TRL scale there are either ideas too immature to be published in scientific articles (TRL 0 and TRL 1) or already commercialized (TRL 8 and TRL 9), thus not targeting the interest of the scientific community, if not even in competition with it.

Going into the details of the four analyzed application domains (see Fig. 13. Technology readiness level (TRL) analysis by educational activity (training or teaching) (left), and for each type of application domain (assembly, manufacturing, design and system configuration) (right) presented in the reviewed articles.), design is the only one who presents a higher number of studies classified as TRL2 than those classified as TRL4. For the assembly and manufacturing domains, TRL4 has two times or more the number of studies than TRL2. System configuration domain does not have any contribution for TRL2. Manufacturing is the only application to present a TRL9 study, which is a VR integrated training conducted in a traditional welding facility [91] that demonstrated how VR could be a valuable tool for efficiently training more skilled welders in a shorter time than with traditional training. This is just the top of the iceberg; the main corpus of works focuses on application that are still under development and in the central levels of the TRL scale.

5. Discussions

This study presents a comprehensive literature analysis to examine current significance of XR technology implementation in manufacturing environments, both in education institutes and in the framework of industry. Given the recent rapid development of the technology, most of the works collected in this review come from the last few years. It might also be a sign of the impact of the recent COVID-19 pandemic on education, promoting the expansion of distance/virtual approaches to teaching and training. The ability to visualize information, replace physical presence and stimulate interaction are key attributes that make XR already an essential part of educational programs, and will in the future be ever more important, given the increasing presence of blended learning programs in higher education. In the industrial framework, such technologies already have an impact on training operators, especially for assembly tasks, which is the field where most of the applications have been developed, and which most of the research has focused on.

This systematic literature review is based on four main research questions; thus, we discuss the results for each of them in the following subsections.

Fig. 13. Technology readiness level (TRL) analysis by educational activity (training or teaching) (left), and for each type of application domain (assembly, manufacturing, design and system configuration) (right) presented in the reviewed articles.

5.1. Discussion around RQ1

The first research question focuses on the existing applications and their goals in manufacturing education with XR technologies.

In the section Applications, as highlighted in Fig. 8, the sample of papers is split in two equally big sets (teaching and training), with 39 papers talking about workers' training and 39 mentioning teaching activities, showing how both are regarded by researchers with equal importance. On the other hand, the most investigated field of manufacturing is assembly. Using VR and AR technologies concurrently on an assembly line for real production seems to be challenging — mostly due to problems derived from being constantly immersed in a virtual world and wearing head-mounted displays for a full shift. The easiest way to help operators with assembly operations is to have superimposed instructions and support information directly on the workspace.

Other common steps of the production process are studied as applications for XR, starting from the design procedures down to the system configuration and the actual manufacturing of parts. Applications are developed for such processes as welding and casting, though rarely research is afterwards deployed in the actual industrial systems, except for one welding product. Also explored is the category additive manufacturing: though not a classic production technology, it has gained importance and recognition and, along with the visualization technologies hereby presented, it could be a growing crucial field of investigation for researchers.

More applications have been developed for maintenance operations, safety protocols, and quality assurance, among others. Safety improvements for operators, machines and systems is also one of the goals that the papers collected in this review wanted to achieve, given the intrinsic value of XR technologies of taking risks away from the manufacturing world. However, new and unforeseen issues arise when using head-mounted displays or enhanced graphic tools: underlying consequences such as headache and nausea need to be accounted for. So, researchers and industrial stakeholders need to find the best trade-off for health and safety, when using XR. In maintenance and quality assurance activities XR can help guiding workers while they are performing their tasks, thus the goal of enhancing skills for operators that emerges from research.

The most sought-after goal for educational activities in manufacturing is knowledge transfer (see also Fig. 9). It means trying to build knowledge for different people (students, operators, experts, etc.), with different teaching instruments. The aim is to either convey declarative knowledge or – most of the time – transferring procedural knowledge that manufacturing processes require. Thus, young students can better understand the subject, or operators can learn new procedures.

Reducing time and cost is a primary goal in the industrial world: it is related especially to the training process of operators. If training can be performed without direct supervision of an expert worker, and without using the same assets that are needed for production, savings in terms of production time and money are worth considering. This is the reason for the extended research in XR guided training of operators, which can be performed with limited or no supervision.

On the other hand, to create skilled workers and competent professionals starting from a young age, the contribution of educational institution should start by stimulating the interest of students towards learning, then providing the correct type of education that comprises both theoretical and practical activities. To reach these goals, since it is often difficult and expensive to have the real tools and resources available for schools, XR technology provides a decisive contribution and can be the instrument that helps bridging the gap between studies and the work environment. Lab activities, dangerous manufacturing processes such as casting and welding and other tasks in assembly, PLC programming, lean activities can all be explored and investigated through use of virtual tools, even in an academic environment.

5.2. Discussion around RQ2

The second research question focuses on the main development tools used in manufacturing education with XR technologies.

In Section Development tools, several hardware and software components of XR technologies found in this literature review are listed. Among the main findings of this review, we show that the development of XR applications follows the pipeline that we proposed in Fig. 10 and analyzed step by step. For each phase, namely, modeling, world registration, rendering and interactive registration, different types of software play a key role.

In modeling, we found a trend in using either manufacturing-specific or generic CAD software. Manufacturing-specific CAD software has a large role on simplifying the modeling of manufacturing tasks, as it provides built-in elements that can be deployed. On the other hand, part of the researchers adopted the largely known multi-purpose CAD software, because it allows building fully customized models, or because there are more free software tools built for general purpose than for manufacturing-specific modeling.

In world registration, we outlined how this operation is often connected to the use of established libraries that are open-source or promoted by the major operative system providers such as Microsoft, Apple, Google, etc. These libraries largely simplify the world registration task and are, therefore, preferred to ad hoc programming.

In rendering and interactive visualization, we found out that Unity, a game engine, is the most used software to produce effective XR applications. Alternatives, such as Unreal or application-specific frameworks, are rarely selected, most probably due to the greater difficulty in deploying the applications on several types of devices at once, and to have the same ratio of good output quality and easiness of programming.

Regarding the hardware, we found out that the most adopted devices are immersive HMDs, followed by any forms of glasses, including AR glasses. The explanation can be that, while the experience of VR can beat any other forms of XR experiences for its immersiveness, and it requires less effort to register its elements in the virtual world instead of the real one, in manufacturing tasks it is often necessary to not lose the external view of the manufacturing environment, or even impossible to render their full complexity in virtual environments. We also noticed

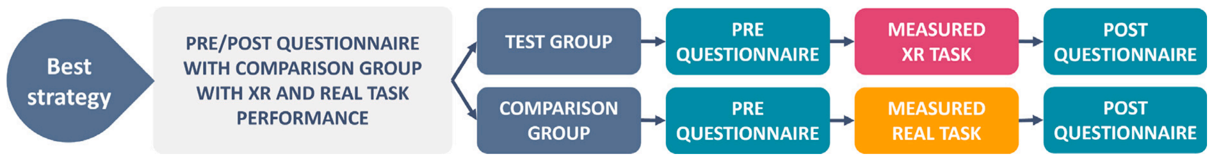

Fig. 14. Most comprehensive (best) experimental strategy. Pre/post questionnaires, test and control groups, and measured performance on both the XR and real tasks.

how there is a prevalence of applications adopting solely either VR or AR devices. Future applications should try to exploit the benefits of XR applications, making use of the entire reality-virtuality spectrum.

5.3. Discussion around RQ3

The third research question focuses on the main experimental strategies applied in manufacturing education with XR technologies.

By looking at the results presented in Section Experimental strategies, we can see that there is no prevalent strategy that is adopted by all the researchers. Not even a debate around a most efficient one. We have listed all the possible alternatives found in the articles and outlined the most common ones. In this section, we also propose the most comprehensive strategy.

There are mainly three elements in an experimental strategy for XR technologies: the use of pre and/or post questionnaires, the ability to record experimental observations directly from the use of the XR devices, and the use of test and control/comparison groups for the experiments. From the observation of these elements, we noted that there are no articles that have used an experimental strategy that merges all these three characteristics. Thus, a complete strategy could be proposed such as to merge strategies D, E and H: pre/post questionnaires, test and control groups, and measured performance on the tasks (including the real one that is not measured in D, E or H). Fig. 14 shows the most comprehensive (best) experimental strategy that we suggest to use for future XR application deployment.

It still remains a point of discussion that the most comprehensive strategy could also be the most efficient one. While this best strategy covers all the possible ways to experimentally assess the impact of an XR technology on education, strategies A, B and C alone are somehow simpler but still effective experimental strategies.

The use of standard pre and post questionnaires, e.g., NASA-TLX, SUS, SSQ and PQ, shall be preferred to the use of customized questionnaires; nonetheless the latter shall be adopted to assess further details of the experiment.

The adoption of control/performance groups is already common practice in other fields, e.g., medical experiments, and can be easily adapted for experimenting with XR technologies. One element of success is the recruitment of large amounts of homogeneous participants to split in test and control groups. While the gender or demographics might play a lesser role in education, it is of the utter importance that the level of expertise of the participants is pre assessed or known before the experiments.

The measurement of performance directly embedded in the XR technologies could help improving the effectiveness of the experiments, and constitute a step towards continually monitoring the performance of such technologies under daily use, rather than limited to experimental setups.

A final remark needs to be done about the necessity of finding better performance indicators for real-to-XR task comparison, especially when using test and control groups, or even XR-to-XR application comparison. As, for example, mentioned by Funk et al. [95], "comparing [assembly] instructions across different papers is nearly impossible because the used measures e.g., task completion time or number of errors, are task-dependent and cannot be easily compared across different [real or XR] scenarios. In order to address this problem, better models are needed – and a basic precondition for the construction of general models is a means for comparing the performance of different systems."

5.4. Discussion around RQ4

The fourth research question focuses on the technology readiness level of the XR applications in manufacturing education.

Since XR technology is relatively new, with viable tools available to the public from around the year 2016, it is expected that its contribution towards education in the manufacturing domain would not yet be industrially developed. The TRL classification of the articles shows this trend, with the distribution centered on TRL 4, i.e., small-scale prototypes developed in a lab and not properly tested (see also Fig. 13). Also, a higher concentration on TRL 2 and 3 rather than TRL 5 and 6 shows that improvement and research are still needed to really make XR technologies daily exploitable for education, which would give a decisive push to blended learning programs in universities.

Looking at the TRL score of the proposed applications, the assembly and the manufacturing domain already started moving towards industrial applications, since a high number of prototype level applications was under development in the past few years. The system configuration domain has no significant low readiness contribution, meaning that XR applications will potentially soon be introduced to the market. On the other hand, the design domain has relatively few mid-to-high TRL contributions and many works in the low readiness levels, showing how it still requires time and research to develop into a marketable product.

The distribution of TRL scores also provide the indication that – given the rapid growth in capabilities of hardware and software tools and the interest that such technologies attract – new and updated reviews on the state of the art of XR for manufacturing education will be needed in the years to come.

5.5. Limitations of this review and future work

Since this review focuses on established and mature technologies, such as AR and VR, we decided not to include more recent terms such as "metaverse", that researchers are currently making efforts to define. The foundation of this research dates back to 2020, when the term "metaverse" had not yet gained widespread recognition. Consequently, our decision to concentrate on established and mature technologies, notably AR and VR, derived from the technological landscape at that time. We acknowledge this limitation as a natural consequence of our study's historical context.

Another limitation is that we focus more on the visual experience of XR technologies, while future studies should include more specifically the other sensorial experiences such as haptic or olfactory.

Concerning the XR technologies employed for the educational purposes, we focus the review on the main hardware and software components. Future works should focus on additional aspects such as data, network, user interface, sensors, actuators, security, and support.

While it is desirable to get meaningful insights on the design of experiment methodologies applied in each article, we realized that almost all the presented researches did not make use of any experimental designs. The basic experimental strategies dealt with participants' questionnaires and when to deliver them, or with *a posteriori* details of experiments such as composition of the randomly recruited participants in terms of gender ratio, educational level, etc. Thus, we limited ourselves to outline what looks like the most comprehensive (best) experimental strategy in this context but, in future studies presenting XR technologies, it would be opportune to provide results based on standard design of experiments.

In the light of the strongly practical side of XR applications, we acknowledge the importance of considering a broader scope in future research endeavors. It would be beneficial to expand research inquiry beyond the existing literature to also encompass a comprehensive examination of industrial applications and their goals, though the amount of time and resources to dedicate to such a project is high. While our current manuscript focuses primarily on the analysis of existing research articles, we recognize the potential value in including industry applications that may not have been covered in the literature.

Finally, our review looked at the overall adoption rate of XR technologies in manufacturing education by means of TRL measurements of the published applications. Thus, by applying a standardized review method, we might have missed out on other aspects of technology adoption. For example, future works should include an analysis of the psychological responses related to users' willingness to accept any XR methods for manufacturing training.

6. Conclusions

This article presents an exhaustive and systematic review of the state of the art in XR technologies applied to manufacturing education and training. We performed a rigorous analysis of the domains, methods, experimental designs, and applications of the reviewed articles. The domain of XR applications in manufacturing learning and training grows rapidly, and further periodical reviews will be necessary. At the time of this article's writing, we have already noted the publication of new relevant papers that were not included in the original search query. A factor that is pushing the recent growth of this domain is the latest innovation happening with XR technologies and the rising computing power of largely distributed small devices. Yet, given the haphazard nature of these technological innovations, the main contribution of our research is to describe a solid methodological framework for the experimental design, measurement and deployment of XR applications in learning and training. In the discussion, we have proposed rigorous methods to address the in-depth research questions regarding knowledge acquisition and transfer through this technologically-enhanced learning modality. The second most relevant contribution of this work, despite the fast pace of the XR technologies and the amount of new research articles on the topic that will make it quickly obsolete, is the state of the art of the research on the use of XR technologies in manufacturing education. Our readers can take advantage of the best practices that we reviewed and presented in this field, and even generalize them around XR-aided education in other disciplines.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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