EXTENDED REALITY IN INDUSTRY: PAST, PRESENT AND FUTURE PERSPECTIVES

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ABSTRACT

The industry's interest in Virtual and Augmented Reality (VR and AR) technologies started from the beginning of their appearance in the research world. Over the years, scholars observed ups and downs, to which various factors contributed. In recent years these technologies, now known as eXtended Reality (XR), have returned to fascinate the industrial world, mainly because most of the related enabling technologies have improved to the point of pushing companies to re-invest in them. The introduction

of approaches such as the digital twin one and the recent hype on the metaverse is also a push in this direction. A few questions arise: what are the benefits of such technologies in the industry today, and what are the unexplored possibilities? Starting from a systematic literature review and exploring the practical implications of integrating technologies in the industrial field, the paper tries to answer these questions. The paper is not intended as a technological forecast but as a stimulus for future research.

Keywords: Virtual reality, Training, Industry 4.0

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1 INTRODUCTION

All over their history, virtual and augmented reality (namely VR and AR) technologies have been introduced in the industry to solve a variety of problems more efficiently, more effectively, or simply in a different way. As Azuma points out in a recent survey (Azuma, 2016), which updates a previously popular one (Azuma, 1997), other sectors did not benefit from these technologies, with the exception of research labs. One of the main reasons was the high cost of the technology. Besides, the technological level of the available solutions was not particularly high at that time.

In the early years of VR/AR, there was no real adoption of these technologies to replace current practices in industry because they did not prove capable of solving problems more efficiently and effectively. Additionally, the implementation of VR/AR applications was not economically convenient, so the latter did not prevail over the former in a balance between costs and benefits.

In the following years, VR/AR technologies have undergone various waves of interest and embraced other application areas. The world of video games, and entertainment in general, initially showed an interest in VR technologies (Nintendo in the late 80s, Sony and Microsoft more recently), and AR did the same later (Rauschnabel et al., 2017). More and more examples of the use of VR/AR technologies have been proposed, which mark the end of their confinement to the industrial and research fields, and which pave the way to the mass market.

It happened that technologies developed in specific areas turned out to be of interest to the industrial sector. Examples are the devices produced by Facebook (Meta), which, despite being born for the world of entertainment linked to social networks, have performances that make them suitable for industrial applications. For example, the Microsoft Kinect device has been used as a gesture recognition technology (Zhang, 2012) and as a tracking system in several examples of ergonomic analysis tools (Diego-Mas and Alcaide-Marzal, 2014). The Nintendo Wiimote controller is another example of an interface designed for gaming and used in several industrial applications (Wingrave et al., 2009; Francese et al., 2012). The trend known as Industry 4.0 started approximately in 2014 and prompted several companies to get interested in VR and AR. Industry 4.0, in fact, indicated AR among the enabling technologies for the 4th industrial revolution (Lasi et al., 2014). The time seemed right for a new wave of interest in VR/AR. In the meantime, the quality of the technology had improved, and prices decreased due to the availability of low-cost displays with high-quality images and microprocessors, MEMS sensors, and so on. Several devices were in the consumer market through large-scale distribution channels (online commerce and traditional shops). It appeared that this technological field had entered a phase of mass market deployment to be used in applications with higher technology readiness levels (TRL). Therefore, the use of VR/AR technologies was spreading in many application areas, as well as in the research field. Furthermore, VR/AR were no longer considered laboratory technologies, not even in the common vocabulary.

However, while expectations were high, they were sometimes let down. Consequently, despite the considerable potential interest from companies in these technologies, they have never really entered industrial practice. Many reasons that have contributed are still linked to the limits of technology and the difficulty of demonstrating its actual advantages. However, there are areas in which these technologies continue to show their usefulness (Boyd and Koles, 2019), both actual and potential, and some companies continue to believe they can benefit from them. In fact, the industrial world, together with the research domain, in a small number of areas, are still making an effort to try to take advantage of them. This becomes evident from the analysis of the scientific literature of the last years.

The new wave of interest is linked to two aspects that have taken hold in the industrial sector. The first is that of the digital twin, intended as the digital model of a real product that embeds data from the real world and updates itself accordingly. There are many definitions of a digital twin. One of those considers it as an extension of a digital mock-up, which has subsequently evolved into a virtual prototype (for a discussion of how digital mock-ups became virtual prototypes see (Bordegoni and Rizzi, 2011)). Regardless of the use of a single definition, when speaking of aspects regarding visualization and interaction with data or 3D geometries, VR and AR technologies are considered appropriate enabling technologies. Using more current terminology, we refer to XR (eXtended Reality) technology. XR has recently aggregated the two terms VR and AR (Cárdenas-Robledo et al. (2022) recently proposed a review on this topic), as VR and AR have always had several aspects in common because scientific communities are often crossed, and also because some devices now allow us to switch between virtual and augmented worlds easily and seamlessly.

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The further push towards adopting VR and AR comes from media success and significant investments related to the Metaverse. Initially introduced in science fiction literature, this term has started appearing in the research world in recent years (Dwivedi et al., 2022). It has become popular since Facebook changed its name to Meta, explaining that the change was related to the company's investment in a new concept, i.e., Metaverse. While the expectation is high and so is the risk of failure, and while there are different interpretations of what the Metaverse is, in some areas, we are already seeing the potential advantages of using the Metaverse. Such practices are already starting to take hold.

Given these premises, it would be interesting to understand which application areas in the industrial sector have not suffered a collapse of interest during the various waves; what are the areas on which to direct the new research, what aspects of the growing interest in the Metaverse can be exploited to guide our future research activities.

This paper intends to answer these questions by crossing the scientific trends of recent years and the experience of the authors in this sector. We conducted a systematic literature review of the past decade from a searchable database, SCOPUS. Then, we identified the correlations between industrial applications and VR and AR technologies and tried to identify any new approaches, technologies and related trends. Finally, we crossed the analysis with the experience gained over the years. We developed a framework that allows us to guide future research activities related to the use of VR/AR technologies in industry.

2 SYSTEMATIC LITERATURE REVIEW

The literature review process consisted of two phases of selection and analysis of documents and keywords related to technologies, application areas, and approaches recurring in the industrial context. In the first phase, the analysis was conducted by considering the documents occurrences related to technologies and application areas separately, while in the second phase, the keyword co-occurrence analysis was conducted by considering together technologies, areas, and approaches. The academic database SCOPUS has been selected for conducting both phases of analysis. To identify as many eligible studies as possible, the different search terms used have been identified and combined with Boolean operators, as described below. The term industr*, representing the context of the analysis, has been constantly considered throughout all the analysis conducted.

2.1 First analysis: documents occurrences

The first analysis aimed to understand the number of scientific documents related to technology integration and advancement in the industrial context in the last ten years, considering specific application areas, such as assembly, maintenance, and training. Different technologies have been selected and searched to obtain comparable data. Starting from the search industr* AND (training OR maintenance OR assembly), each technology considered between virtual reality OR vr, augmented reality OR ar, mixed reality OR mr, extended reality OR xr, has been added to obtain four different queries searched in article title, abstract, and keywords fields on SCOPUS. Then, exclusion criteria were used to shortlist and screen the list of papers obtained. The search was limited to the following papers: English language, journal articles, and conference papers published between 2013 and 2022. Each search produced an analysis of the results on SCOPUS that indicates the occurrences of documents related to different technologies in the last ten years. The obtained graphics have been extracted and compared, as shown in Figure 1.

The chart highlights that the interest in technologies such as AR and VR has been growing through the years, especially since 2018. In particular, VR is confirmed as the most cited technology among the mentioned, appearing in 146 documents in 2022. In addition, the extracted data shows that the term extended reality OR xr seems not very cited compared to others, revealing the tendency to define the specific technology rather than the general belonging category.

VR is increasingly used, finding applications both in the assembly, in maintenance, and especially in training. Indeed, thanks also to its capability to facilitate the visual understanding of complex concepts (Checa and Bustillo, 2020), VR has started to offer a risk-free manufacturing scenario to train employees (Lin et al., 2002), so that virtual reality training became an increasingly frequent concept within the literature.

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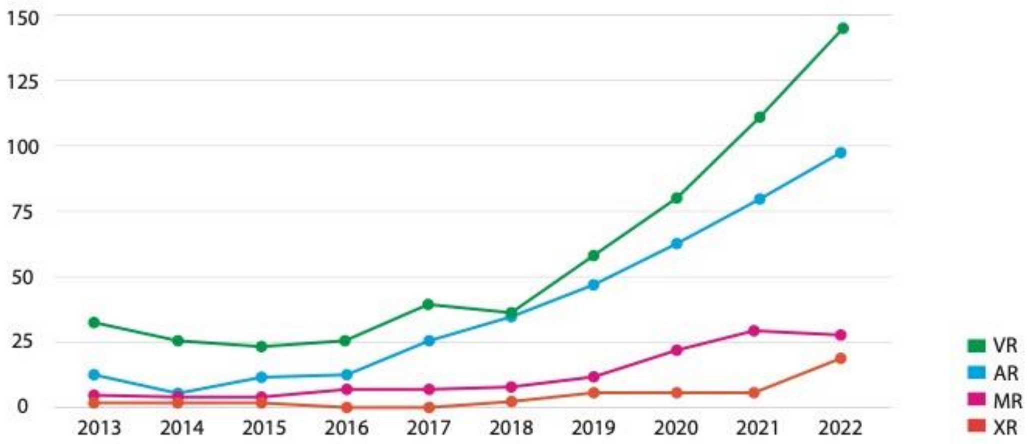

Figure 1. Occurrences of documents by year related to different technologies and the considered application areas in the industrial field.

Similar research has been carried out by combining the technologies previously analyzed and isolating the application areas chosen for the industrial sector. In this way, three search criteria have been adopted. As an example, one of the adopted search criteria was: industr* AND training AND (virtual OR augmented OR mixed OR extended) AND reality OR (vr OR ar OR mr OR xr). Moreover, the same exclusion criteria reported above, related to the type of document, language, and years restrictions, have been used.

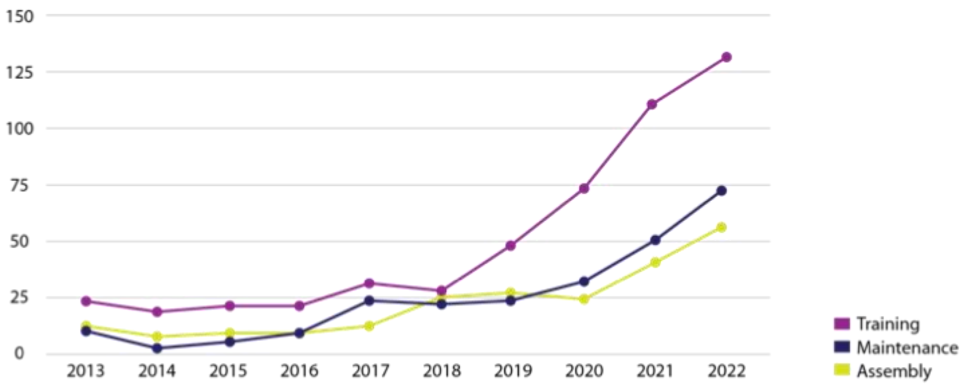

Figure 2. Occurrences of documents by year related to different application areas and the considered technologies in the industrial field.

As shown in Figure 2, the training application area has grown exponentially since 2018, much faster than both assembly and maintenance ones. In fact, as previously mentioned, Virtual Reality training is frequently used within the industrial field. This aspect can be linked to the increased adoption by companies of XR technologies for applications related to safety and health in the workplace. Indeed, virtual training applications can help in reducing the risk or the possibility of accidents and fatality in the workplace and in safeguarding employees.

2.2 Second analysis: keywords co-occurrences

In the second phase, to pursue a more in-depth analysis of the literature considering the keywords cooccurrences, the Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines (Wittorski, 2012) have been adopted. These guidelines provide a standard methodology that contributes to the replicability of the review process. Starting by using the same search criteria previously adopted, the data extracted have been analyzed to obtain a graphical network of the keywords co-occurrences during the last ten years. The approach followed is explained in Figure 3.

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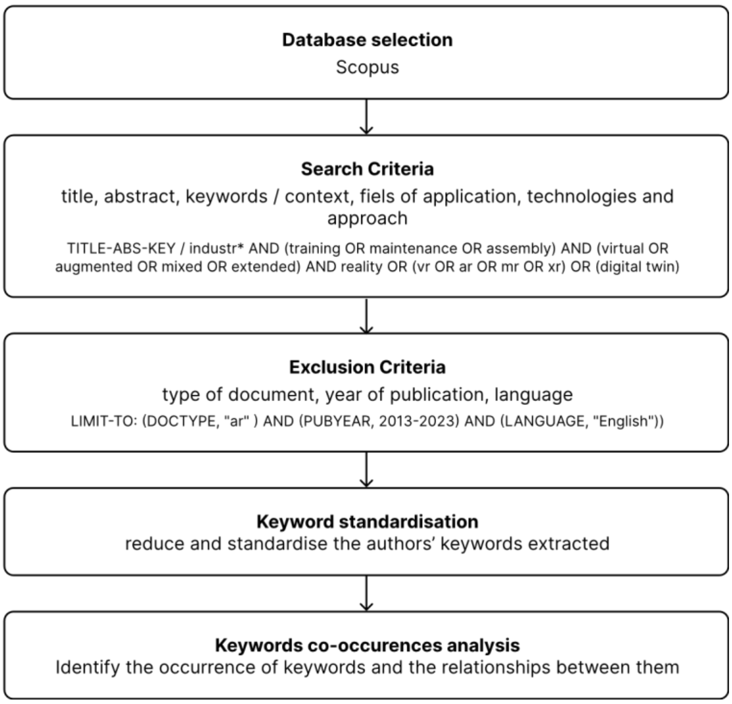

Figure 3. Methodology adopted for the second analysis of the literature.

As for the first step of the process, the search criteria have been defined by putting together all the aforementioned concepts related to technologies and application areas within the industrial context. Moreover, the digital twin approach has been added to the search criteria, being considered an interesting topic for this second analysis. The search criteria adopted were the following: industr* AND (training OR maintenance OR assembly) AND (virtual OR augmented OR mixed OR extended) AND reality OR (vr OR ar OR mr OR xr) OR (digital AND twin). As in the previous analysis, SCOPUS has been used as the database for conducting the research by selecting the article title, abstract, and keywords field. The search results obtained at this stage were 4,124 papers. These results were filtered using the exclusion criteria already adopted in the first analysis. The exclusion criteria allowed us to limit the dataset to 837 papers, consisting of journal articles in English, published from 2013 to 2023 (in this case, also 2023 has been considered, offering few useful results for the keyword co-occurrences analysis). This database was exported from SCOPUS into CSV format, including information about the title, authors, publication year, and authors keywords for each paper. Then, to avoid repetitions and to standardize the data, the authors keywords were reviewed. The keywords were modified in terms of wording (e.g. virtual reality, virtual environment, VR, and Virtual Reality (VR) were standardized to virtual reality, and 3D modelling, Three-dimensional (3D) model, and 3D plant modelling were standardized in 3D modelling), and in terms of meaning (e.g., additive manufacturing and 3D printing have been standardised in additive manufacturing). In this process, the reference keyword was selected based on the popularity of its usage. In addition, the keywords related to specific software or devices were removed from the database (e.g., Unity, Vuforia, Microsoft Hololens) because they were considered not relevant for the analysis conducted. The publication year and the authors keywords, related to each paper, have been then selected to create a network visualisation by using Gephi (see Figure 4).

A network consists of nodes and edges, and this research presents a normal network, showing only one type of node. Each node denotes a keyword occurrence reported in the dataset, while the edge represents the co-occurrence of the keywords in the same year. So, in Figure 4, the node size indicates the frequency of the keyword occurrence, and the edge thickness indicates the frequency of keyword co-occurrence per year. Force Atlas 2 has been selected to determine the layout in Gephi. Moreover, the database has been reduced in size, also excluding those keywords that have less than ten times occurrence.

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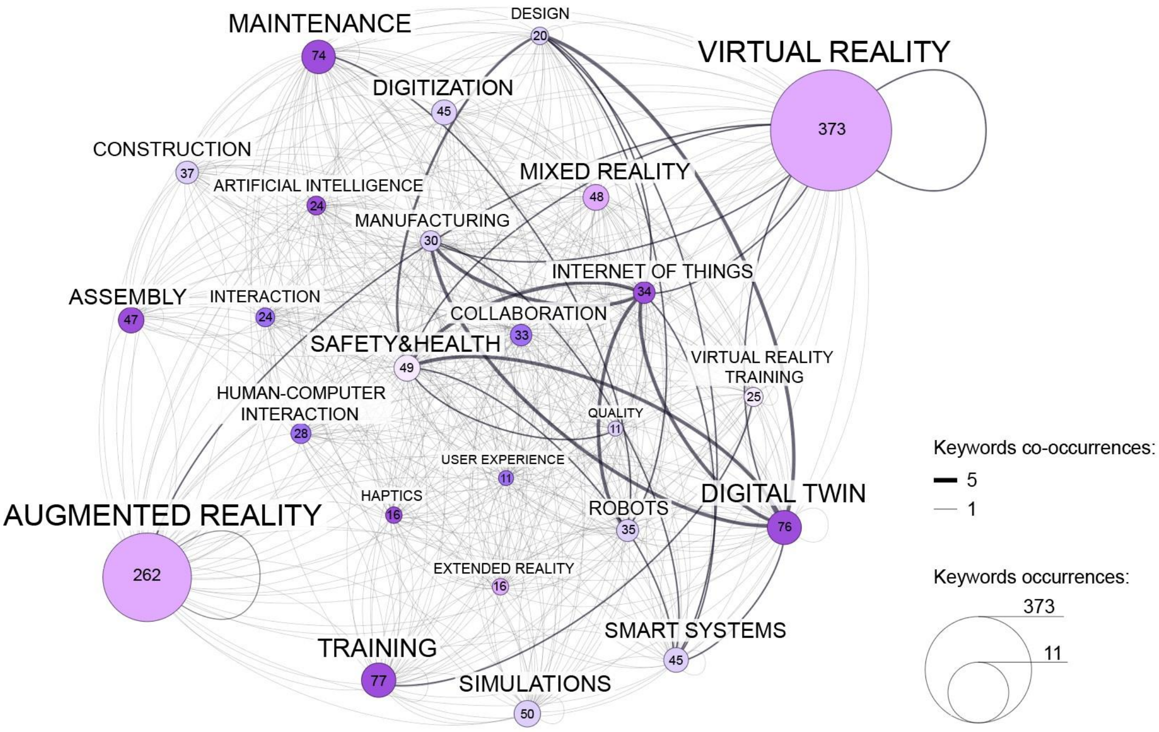

Figure 4. Co-occurrence network keywords related to technologies, areas, and approaches in the industrial context. The node size indicates the number of occurrences of a keyword. Edges between nodes indicate co-occurrences between keywords in the same year.

The obtained network shows that the most recurring keywords are virtual reality (with 373 occurrences) and augmented reality (with 262 occurrences). This result is in line with the first analysis conducted, in which the most cited technologies were VR and AR. Indeed, also in this network, the MR technology is not predominant, having an occurrence of just 48, while the XR technology appears within the network, just presenting 16 occurrences. Concerning the field of application, training confirms its prevalence with 77 occurrences, and the new concept of virtual reality training appears so often (25 times) to be classified as a single node. Despite this, the second analysis shows that the keyword maintenance is also very recurrent, reporting 74 occurrences, demonstrating to be a great field of interest as well. Also, the digital twin approach reveals to be particularly influential, showing 76 occurrences. Other than the main keyword already examined previously, the second analysis also offered the possibility to map other concepts related to the technologies and areas explored. The network showed a great interest in the safety and health domain, which appears 49 times in the database, and that shows also a strong link with the digital twin approach. Other interesting aspects are represented by the presence of keywords such as user experience, interaction, human-computer interaction, collaboration that underline the importance of the quality of the human-machine process. In addition, new types of technologies, much cited in the industrial field, such as artificial intelligence(AI), internet of things (IoT), haptics appear in the network.

3 CURRENT STATUS AND FUTURE OPPORTUNITIES

In this Section, we provide a perspective regarding the use of XR technology in industry. We will cross the results from the literature review with detailed considerations that derive from the authors' experience developed over years of research on these topics. Whenever interesting points emerge from the review, we will identify opportunities and barriers that still limit the adoption of these tools and methods in the industrial world. In doing this, it should be noted that if the goal is to match the needs of the industrial world with the opportunities offered by emerging technologies, it is, first of all, necessary to capture and interpret the real needs that the industries have. Once matched needs with technologies and methodologies that permit fulfilling them a continuous comparison and an effort to find compromises are necessary before they can get adopted.

3.1 Application areas

The analysis focused on three application areas: assembly, industrial maintenance, and industrial training. Except for the entire design review phase, in which VR and AR technologies are already being used as potential and low-cost alternatives to real prototypes, these are the main areas where companies, supported by researchers, are investing more in the use of these technologies.

Regarding assembly task simulations, this topic is rather dated in the literature (Jayaram et al., 1997). Simulating the assembly of system components helps highlight any design issues before the parts are manufactured. Virtual reality has typically been used in this context, and haptic devices, a technology that emerged from the second analysis, have also been developed for this purpose. Despite the availability of CAD geometrical models developed during the design phase of a system, the possibility of transferring this data directly into the VR environment and performing assembly operations in VR is still an open issue. Importing CAD models into VR environments is not always simple; the relationships between the various models that make up a system are not always maintained, just as the collision algorithms typically used in VR are not suitable for handling collisions for assembly simulations. It follows that if we want to continue performing assembly simulations in VR, we need to invest in algorithms that automate the exchange of information between CAD environments and VR environments and improve collision detection algorithms.

Also, while the ability to use the sense of touch through haptic devices increases the realism of simulating assembly tasks, it sometimes makes simulation development complicated and time-consuming. As far as haptic systems are concerned, new wearable interfaces have recently been designed that can partially replace the force feedback devices used in the past in assembly simulations. These new devices sometimes reveal limitations in tracking finger movements and the type of tactile feedback they reproduce. In any case, they are improving their performances as haptic device manufacturers are investing significantly in this direction. It is worth pointing out that the sense of touch is one of the most interesting senses in the Metaverse (Sun et al., 2022).

Maintenance is particularly relevant in industry. In some cases, efficient maintenance service is a value companies use to convince customers to choose their product or system over those of the competition. Therefore, providing an effective and efficient maintenance service is of great interest to companies. It is strategic to have complete and adequate maintenance documentation and, at the same time to keep the know-how internally. In this context, companies have invested in the past in implementing AR applications to support maintenance activities (Henderson and Feiner, 2010; Palmarini et al., 2018). They have experimented with using AR as a standalone application (to replace traditional documentation) or collaboratively in the case of remote maintenance. This second topic is particularly relevant for companies because one of the main problems is providing quick assistance when a product located at the customer has a technical problem. Typically, companies have a limited number of skilled people who can solve specific problems and continuously travel to provide assistance. Remote maintenance support tools make it possible to reduce intervention times and improve the perception of the quality of the maintenance service (Masoni et al., 2017).

One barrier that limits the use of VR and AR technologies for maintenance support is hardware limitation; sometimes, device performances do not meet industrial requirements. However, hardware technology is gradually improving. Another barrier is authoring time - the time and effort necessary to create the digital documentation and to develop the application. The availability of authoring tools (see the work of Gattullo et al. (2019, 2020) for an overview of this topic) and the use of AI algorithms that allow us to analyze data and populate digital manuals would allow us to overcome this problem. As mentioned previously, AI is also one of the technologies that emerged from the second literature review analysis.

Training finds several applications in industry: from knowledge transfer to safety. Also, in this case, one of the main barriers that prevent the full adoption of these technologies is time and authoring effort. We also lack methodologies to measure the effectiveness of the proposed tools and solutions in transferring knowledge and creating skills.

3.2 From XR to the Metaverse

Although there is not a full convergence on the Metaverse concept, it is generally agreed that it is a three-dimensional world populated by digital information that derives from digital and digitized real data (Ball, 2022). In the Metaverse, objects and digitized human beings represented through avatars coexist. As conceived, the Metaverse allows access and sharing of the same experience. This feature is particularly

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relevant for all the applications we saw in the previous section. Both training and maintenance activities, especially remote ones, would greatly benefit from features that enable collaboration. In this sense, the Metaverse could effectively replace the traditional virtual scenarios used so far. The Metaverse could also grant ownership of digital information. This would allow companies to open an additional business starting from the data they have already created in the design phase.

AI technologies can be considered one of the most promising add-ins (Huynh-The et al., 2023). These algorithms would allow us to quickly analyze incoming data, create digital information and control the behaviour of objects and avatars in the scene.

One of the ways to access the Metaverse should be through XR technologies. In this context, many devices are starting to have affordable costs and performances that meet industrial requirements. Typically, the most advanced and industrialized technologies are those for the sense of sight and hearing. The sense of touch, historically little explored compared to sight and hearing, is experiencing a remarkable development. Olfactory technologies, on the other hand, are underdeveloped yet offer considerable potential.

3.3 Potential benefits of XR in industry

The use of XR technologies in industry has many potential advantages, which can translate into benefits for producers and buyers. Below, we analyze the potential benefits companies can derive from using XR technologies in the addressed application areas: assembly, industrial training and maintenance.

The first advantage for machine manufacturers (OEM) and machine users is economic. Training and maintenance can be challenging for some companies or expensive for best practices. A futuristic evolution of industrial maintenance is that of OEM providing maintenance as a service. Thanks to the implementation of Industry 4.0 paradigms and cloud platforms, OEMs can offer maintenance as a service with the purchase of their machinery. The service can consist of technical descriptions, videos, documented maintenance tasks, and training materials. Training material could be in the form of XR training, offered remotely, which can be used directly by the machine operators and even connected to sensors on board the machinery for troubleshooting and prediction. This new model would be beneficial for both manufacturers, which can increase their sales by offering products and services, and machine users, which can reduce maintenance costs and effort.

Improving training has several implications. One impact is on the transfer of knowledge within the company. One of the typical problems of the industrial world is to capture knowledge, codify it and make it available to prevent it from being lost over time. The technologies presented so far would make it possible to solve this problem more efficiently. Think, for example, of the possibility of recording real activities and encoding them through AI algorithms and making them usable through XR interfaces. Efficient training of new employees, based on previous knowledge and practical tools, can reduce the time it takes them to learn the procedures. These aspects refer to an economic advantage for the company.

A second significant impact is on sustainability. Ensuring an efficient maintenance service also impacts the sustainability of the production processes, which is today a very relevant issue for companies (Karki and Porras, 2021).

Today, sustainability has also proved to be an effective marketing slogan for companies which promote their products and brand as active in environmental or societal issues. At the same time, VR and AR technologies have been used to publicize companies’ aptitude for innovation and research. Therefore, somehow XR can also have an impact on marketing.

Eventually, a further benefit concerns safety. Improving operators’ knowledge and skills before performing any technical task can impact safety. XR is an excellent tool for experiential learning in complex topics that are otherwise too risky, expensive, or dangerous. Operators can make decisions that do not affect themselves, others or the organizations equipment.

Now, the question is what is still missing for XR technologies to finally become common practice. In our opinion, the methodologies that allow the XR technologies to be exploited correctly have not yet been adequately developed. There is also a lack of a good cost-benefit analysis that ultimately demonstrates the real benefits.

Figure 5 shows an overview of the analysis carried out. From top to bottom are represented respectively: the areas of application, the enabling technologies, the data they use, and finally, the main benefits that companies derive from their use. This representation intends to provide an overview of the problem just analyzed and to suggest areas of current and future interest for research.

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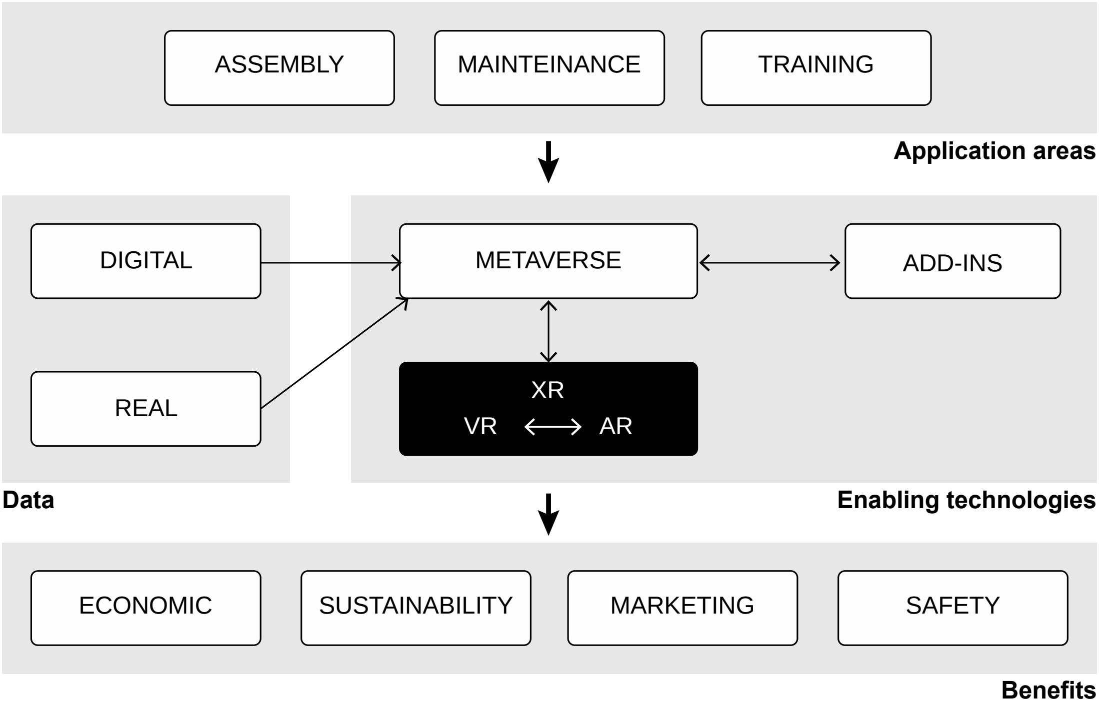

Figure 5. Relationship between technologies, applications and exploitation

4 CONCLUSION

The industrial world has always shown interest in VR, and AR (now XR), even when these technologies were still underperforming. After a series of ups and downs, it seems that the conditions are now all there to allow these technologies to enter industrial practice. In this paper, we aimed to highlight the potential industrial applications that show interest in these technologies. We have made a systematic literature review and analysis considering the last ten years and highlighted the correlations between industrial application areas, VR, AR and XR technologies and emerging approaches and technologies. Following this analysis, we have proposed a series of considerations related to the traditional and emerging issues. These considerations aim to stimulate research activities that allow these areas to finally leave the research laboratories and become standard practices in the industry world. This step requires developing related methodologies and cost-benefit assessments that prove the advantages.

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