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XR TECHNOLOGY IN MANUFACTURING – EXPLORING OF PRACTICAL APPLICATIONS

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Purpose: The purpose of this paper is to provide a comprehensive analysis of the practical applications of Extended Reality (XR) technologies in the manufacturing industry, aiming to identify both internal and external factors that facilitate and inhibit XR implementation.
Design/methodology/approach: The study used a multi-step approach, starting with an extensive literature review covering the latest publications, technology reports and case studies from reputable databases (Scopus, Web of Science, Semantic Scholar) and sources from 2019-2024. The literature review focused on key trends, benefits, challenges, and practical implementations of technology XR in manufacturing. Following this, two complementary analyses – STEEPVL and SWOT – were conducted to examine social, technological, economic, environmental, political, value-based, and legal factors. These methodologies were chosen to provide a comprehensive understanding of the multi-dimensional factors influencing XR implementation.
Findings: This study's primary finding is that XR technology has substantial potential to increase productivity and drive innovation within the manufacturing industry. XR optimizes production processes, enhances training and safety, and supports diagnostics, making enterprises more competitive and flexible. However, its implementation also presents significant challenges, including high initial costs, the need for ongoing personnel training, and the risk of rapid obsolescence. Additionally, external factors, such as legal and regulatory constraints and public acceptance, are critical, as they shape both the pace and scale of XR technology's adoption across different regions.
Research limitations/implications: Although XR technology has diverse applications across various sectors, this study focuses specifically on its use in manufacturing, which limits the generalizability of the findings. Additionally, despite using defined criteria for selecting and classifying factors within the STEEPVL and SWOT frameworks, some subjectivity remains due to the reliance on expert predictions and opinions. These findings reflect the current state of the technology; as XR advances, future assessments of its impact may evolve significantly.
Originality/value: The originality of this study lies in the combination of STEEPVL and SWOT analysis, offering a cross-disciplinary perspective on XR technologies in manufacturing. This approach facilitates a more detailed examination of the factors influencing XR adoption, while the classification of factors as current or potential provides a dynamic, time-sensitive understanding that can better inform industry stakeholders and decision makers.
Keywords: manufacturing, extended reality, mixed reality, virtual reality, augmented reality
Category of the paper: research paper, literature review.

1. Introduction

Digital transformation is the process of integrating new digital technologies into all aspects of an enterprise's operations, fundamentally changing the way business is run, and value is delivered to customers. The Top 10 Digital Transformation Technology Trends are additive manufacturing, advanced computing, AI and machine learning, big data, and analytics, blockchain, 5G, cybersecurity, digital twins, extended reality (XR), and the Internet of Things (IoT). (Start-sup Insights, Manufacturing Trend Report)

Extended Reality (XR) is an umbrella term that includes both Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). (Kaplan et al., 2020; Billinghurst, Nebeling, 2021; Mhaidli, Schaub, 2021; Ratclife, Soave, 2021; Gugenheimer et al., 2022) It involves a broad spectrum of technologies, differing in the degree of immersion i.e., integration with the real world. (Report Tech Trends, 2024) One can think of XR, as a collective name for virtual technologies, both those we know today and those yet to be created, supplementing or replacing the perception of the real world with additional elements from the virtual world. (Figure 1).

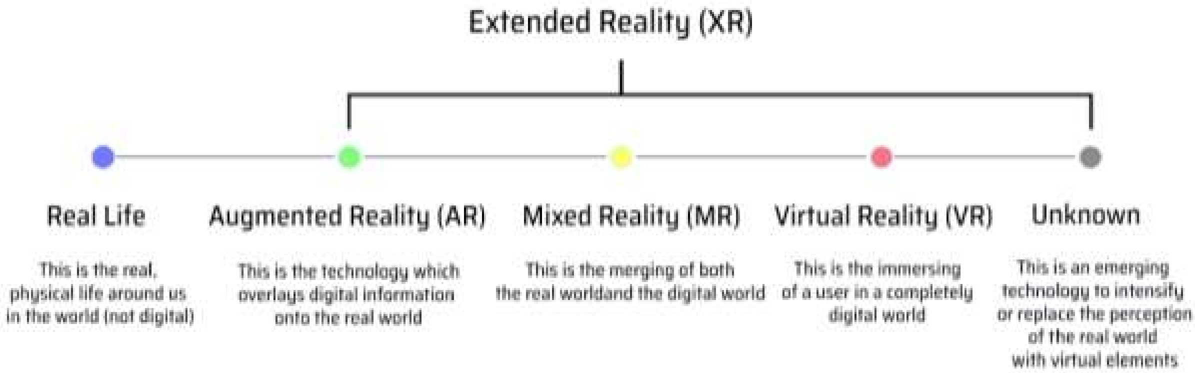

Figure 1. Extended reality spectrum.

Source: author's work based on appinventiv insider.

Virtual Reality is a technology that allows users to enter a completely virtual world, using special VR glasses or helmets. The user is completely immersed in an artificial environment, which can be computer-generated or based on recorded content. On the other hand, augmented reality is a technology that superimposes digital elements, i.e.: images, sounds and animations, over the user's real environment. (Hirzle et al., 2023) Meanwhile mixed reality is a combination of VR and AR. In an MR environment, the user can see and co-integrate with both digital objects and the real environment. The main technological differences are in the level of interaction and immersion. Terminology in the field of mixed reality and extended reality technologies is dynamic and used differently depending on the source. Often the acronyms MR and XR technology are used interchangeably as synonyms, so it is important to understand the context in which the term is used. (Speicher et al. 2019; Doolani et al., 2020) Interestingly, in the literature, extended reality technology is also presented as a subfield of artificial intelligence.

(Habeeb et al., 2024) A key aspect of defining XR is that the term encompasses a broad spectrum of educational experience delivery options, ranging from low-tech, episodic interactions to fully immersive, enduring platforms. (Ziker et al., 2021) Due to its elevated level of immersion and sensory engagement, this technology effectively enhances users' critical thinking skills across various tasks. (Alsaleh et al., 2022) XR technologies fill the gap between the digital and physical worlds in manufacturing. They also fit into the Industry 4.0 paradigm, in which digitization, automation and connected systems are integral to the operation of modern factories. (Cárdenas-Robledo et al. 2022) The integration of physical production processes with advanced digital technologies is supported by XR through the introduction of interactivity, automation, and visualization. They improve manufacturing processes by allowing users to interact and feel involved in the design process, especially through interactive simulations and 3D visualizations (Ismail et al., 2023). The authors (Gac et al., 2019) found that the usability of an immersive tool depends on the clarity and design of the user interface. It can be concluded that intuitive and well-designed interfaces are critical to enhancing user experience and effectiveness in immersive tools, as they reduce cognitive load and facilitate smoother interactions with the technology.

The manufacturing industry is constantly working to increase competitiveness by integrating information technology into key processes. A survey conducted by XRA and RXN Group of 600 CEOs and decision-makers from manufacturing enterprises across the country found that 81% of them believe that immersive technology like XR benefits manufacturing. (Report AR/VR/XR Survey, 2021) XR technologies, which include VR, AR, and MR, play a significant role in this support. The industry is undergoing a transformation from traditional labor-intensive practices to more advanced and integrated systems. Early deployment of XR technologies increases the momentum of work. Integrating XR with other technologies offers deeper insights into manufacturing processes, allowing for better decision-making.

The application of XR in the process of digital transformation of enterprises was presented in the form of a comparative table of selected manufacturing areas (Table 1).

Table 1.
Manufacturing phases and when to use which XR technology

Manufacturing Phases	Tasks	Useful XR Technology
Introductory Phase	Safety, training, orientation training, planning and designing of new tasks	MR, VR
Learning Phase	Sorting, picking, keeping, assembling, installation	AR, VR, MR
Operational Phase	Inspection, packing, monitoring assembly line, assembly	MR,
Tangent Phase	Using rare tool/ machinery, hand tool, power tool	AR, MR
End Phase	Cleaning routine (process, shovel, sweep, clean work areas, inspection)	AR, MR

Source: based on (Doolani, S. et al., 2020, Cárdenas-Robledo et al., 2022).

Augmented reality technology has been proven to be helpful also in areas such as remote assistance, training, facility management or product inspection and design. (Bottani, Vignali, 2019) Also in areas such as visualization (Ferraguti et al. 2019; Angrisani et al., 2020; Alves et al., 2022;) simulation (Cai et al., 2020) tracking and operation (Calandra et al., 2021) assembly (Hoover et al., 2021), maintenance (Havard et al. 2021). In turn, Virtual Reality is used in the field of assembly (Grappiolo et al., 2021; Ottogalli et al., 2021), simulation (Fang et al., 2019; Perez et al., 2019; Huerta-Torruco et al., 2022) Mixed Reality is especially used in the field of assembly (Dimitropoulos et al., 2021, Ariansyah et al., 2022), maintenance (Siyaev, Jo, 2021; Ariansyah et al., 2022), training and simulation (Malik et al., 2020a et al., Malik 2020b).

Mixed reality technology is the most flexible technology, and it can be used in almost any phase. In a production scenario, it can be used for training in any phase because it is not completely immersive like VR and allows the user to see their real world along with digital information. (Doolani et al., 2020). A review (Cárdenas-Robledo et al., 2022) shows that MR is likely to become a dominant technology, supported by various devices such as tablet HMDs and VR and AR-enabled glasses with added physiological and environmental sensors. Furthermore, the development of affordable, user-friendly XR applications is expected to accelerate their adoption in various sectors.

In literature, there are increasingly frequent forecasts about the future of XR in the industry, indicating further technological development and its growing application across various manufacturing sectors. However, while the potential benefits of XR technologies are well documented, their successful integration and implementation in manufacturing is still an area of current research. Stakeholders must deal with various technological, organizational, and user-related barriers.

The author used the method of literature analysis and critique, and did SWOT and STEEPVL analyses, which is an original approach to the study of XR technology in manufacturing. The combination of these two methods provided a more multidimensional insight into the internal and external factors affecting the implementation of XR technology, considering environmental, technological, social, economic, legal, value and local aspects. This approach, which is rare in the literature on XR technology, especially in an industrial context, makes the work novel. Internal strengths and weaknesses, as well as external opportunities and threats related to the implementation of augmented reality technologies in production are identified. In addition, the paper considers future potential scenarios for XR development, considering the dynamic nature of technological progress and the changing regulatory and social environment.

The paper includes an introduction, a review of national and foreign bibliography and technology reports, a description of the methodology and a discussion. It ends with a summary, which additionally considers potential trends that may influence the development of XR technology soon and suggestions for further research.

2. Methods

The initial phase involved an in-depth literature review to establish the theoretical and practical foundations of XR applications in manufacturing. Relevant scientific publications and technology reports from 2019 to 2024 were collected, with a focus on the manufacturing industry. The review highlighted key trends, potential applications, and challenges related to XR in manufacturing.

A STEEPVL analysis was then conducted to assess the long-term, multi-dimensional impacts (social, technological, economic, environmental, political, value-based, and legal). This was followed by a SWOT analysis that provided a comprehensive understanding of both internal and external factors influencing XR implementation. The selection of methodologies aimed at balancing depth with breadth, and the complementary nature of SWOT and STEEPVL helped provide a structured and nuanced perspective for industry stakeholders.

3. Results

This paper presents the results of two research methods: STEEPVL analysis (Table 2) and SWOT analysis (Table 3), which in the previous chapters were enriched with a review of the subject literature.

Table 2.
STEEPVL analysis of XR technology in manufacturing

Category	Current factors	Potential factors
Social	Younger employees are more open to implementing innovative technologies, which can facilitate the implementation of XR in the workplace.	As organizational cultures evolve to embrace innovation, the acceptance and integration of XR technologies are likely to improve.
	Older employees may resist XR due to a lack of familiarity and comfort with innovative technologies, posing a challenge to widespread implementation.	As technological literacy improves across all age groups, resistance to XR from older employees may decrease, aiding broader implementation.
	The shift towards remote work can increase the demand for XR technologies to facilitate virtual collaboration and training.	XR can provide intuitive and engaging training tools that bridge generational gaps in the workplace.
Technological	The combination of XR with IoT and AI enhances the ability to monitor and optimize production processes in real-time	Edge computing can enhance XR performance by processing data locally, reducing latency and improving real-time responsiveness.
	The absence of standardized protocols and frameworks for XR technology can create compatibility issues and hinder its broad implementation.	The establishment of industry standards for XR technology will facilitate better integration with existing systems, promoting wider implementation.

Cont. Table 2.

Category	Current factors	Potential factors
	The deployment of 5G networks can significantly improve the speed and reliability of XR applications, enabling more seamless and responsive experiences.	XR can integrate with technologies like blockchain for secure data transactions and digital twins for advanced simulations, expanding its capabilities and applications.
Economic	Increased funding and support for Industry 4.0 initiatives can drive the implementation of XR technologies in industrial settings.	XR can facilitate the creation of personalized products, tapping into niche markets and generating new revenue streams.
	The significant upfront costs and the rapid pace of technological change can make XR investments risky and expensive to maintain.	Economic instability can influence the willingness and ability of enterprises to invest in XR technologies, slowing implementation.
	Remote working and virtual meetings with XR support can reduce the need for travel and physical office space, leading to significant cost savings.	Government incentives can lower financial barriers for enterprises, encouraging investment in XR technologies.
Ecological	XR can help optimize manufacturing processes, reducing waste and environmental impact.	Strict environmental regulations can encourage enterprises to implement more energy-efficient XR solutions to meet sustainability goals.
	XR can enable virtual prototyping and testing, reducing material waste and energy consumption in the development process.	Advances in energy-efficient technologies can help mitigate the environmental impact of XR systems.
	The energy-intensive nature of XR systems can increase the environmental footprint and costs.	Using renewable energy sources to power XR systems can further reduce their environmental footprint.
Political	Data protection regulations can restrict how XR technologies process and store personal data, which impacts their functionality.	The right regulatory framework can encourage the adoption of XR technologies by providing an enabling environment for innovation.
	Trade policies can impact the supply chain and pricing of XR components, thereby affecting their availability and affordability.	Global collaboration can help establish common standards and promote widespread implementation of XR technologies.
Values	Innovative enterprises are more likely to adopt XR technologies to gain a competitive advantage.	An emphasis on ethical data practices and social responsibility can shape how XR technologies are implemented and used.
	XR provides accessible tools for training and collaboration, supporting integration initiatives.	XR can offer broader support for training, facilitating integration and equal access to professional development.
Legal	Compliance with stringent data privacy regulations can pose a challenge for XR implementations, requiring the use of robust data protection measures.	New cybersecurity regulations may require enterprises to enhance their security infrastructure, increasing the cost and complexity of XR implementation.
	The creation and use of virtual content in XR environments can raise complex intellectual property issues that need to be addressed.	Legal frameworks tailored to XR technologies can help address unique issues and promote responsible use.

Source: author's work based on literature review and analysis and technology reports.

Furthermore, organizational leadership plays a critical role in shaping this acceptance by promoting a culture of innovation and offering mentorship programs to guide employees of all ages through the technological shift. Encouraging a growth mindset across all employee demographics can bridge generational divides, easing the integration of XR technologies. Additionally, the rise of remote work further increases the demand for XR, especially for virtual collaboration and training, as enterprises seek ways to maintain productivity and communication across dispersed teams.

Establishing industry standards for XR will be key to overcoming these barriers and ensuring that XR technologies can integrate seamlessly with existing systems. Moreover, the deployment of 5G networks has the potential to revolutionize XR applications by providing faster and more reliable data transmission, enabling smoother and more immersive XR experiences. Future integrations could expand XR's capabilities, such as combining blockchain technology for secure data transactions or using digital twins for advanced simulations in manufacturing, leading to more efficient and transparent production systems.

From an economic perspective, the implementation of XR technologies requires substantial investment, which can be a significant challenge, particularly for small and medium-sized enterprises (SMEs). They struggle with the high upfront costs of XR, including hardware, software, and necessary infrastructure. Government incentives, such as grants or tax incentives, can help mitigate these costs, making XR implementation more accessible. Larger enterprises, while having more financial resources, still face challenges related to scaling XR solutions across multiple sites. These enterprises may also have competing priorities for their capital expenditure, such as investments in IoT or AI. Alleviating the financial strain, enterprises can explore options like leasing XR hardware, entering pilot programs with XR vendors, and collaborating across sectors to share resources and reduce costs. Additionally, XR technologies offer the potential to create new revenue streams, such as personalized products or on-demand manufacturing services, which can offset the initial investment by opening niche markets.

The energy-intensive nature of XR systems, particularly in data centers and 5G infrastructure, increases the environmental footprint due to reliance on non-renewable energy sources and rapid hardware obsolescence. To mitigate these impacts, enterprises can use renewable energy, adopt energy-efficient hardware, and utilize cloud-based XR solutions. Additionally, virtual prototyping can reduce waste, while promoting recycling and responsible disposal of outdated XR devices helps address electronic waste concerns.

The political and legal landscape significantly impacts implementation of this technology. Data protection regulations require robust measures, complicating its implementation, while trade policies affect the cost and availability of components. Legal issues, such as intellectual property rights for digital assets, also pose challenges. Tailored legal frameworks and government support can help address these concerns, fostering innovation and creating a conducive environment for approval XR technology.

The results of the analysis constitute valuable input material for the SWOT analysis (Table 3), to facilitate the identification of opportunities and threats. SWOT analysis allows for understanding the strengths and weaknesses of XR technology and identifying opportunities and threats that may affect its use in manufacturing.

Table 3.
SWOT analysis of XR technology in manufacturing

Strengths	Weaknesses	Opportunities	Threats
Increased precision in production planning and monitoring	High initial financial outlay for XR equipment, software licenses, and IT infrastructure adaptation can be a significant barrier to entry, especially for smaller enterprises.	Intelligent XR training programs using AI for personalized training can enhance learning outcomes and efficiency, adapting to individual user needs.	The risk of personal data leaks and manipulation by enterprises or malicious actors poses significant security and privacy concerns, potentially hindering implementation.
The continuous development of XR technology and increasing market interest	Integration issues with existing systems can pose significant challenges, requiring additional resources and time to resolve compatibility problems.	Potential government incentives and funding opportunities for implementation advanced technologies like XR, which can reduce financial barriers and encourage investment.	Changing legal regulations and data protection standards can impose additional requirements on XR systems, increasing compliance costs and complexity. This can deter enterprises from implementation XR technologies.
Interactive training with real-task simulations minimizes error risks and ensures faster adaptation of new employees to processes.	The need for robust technical support and maintenance services to ensure the smooth operation of XR systems, which can be resource intensive.	Expanding niche markets for personalized products with XR, increasing the enterprise's revenue potential and geographic reach.	The rapid pace of technological advancement in XR can lead to the quick obsolescence of current solutions, necessitating frequent updates and replacements. This can significantly increase operational costs and create financial strain.
Remote diagnostics and support enable immediate service assistance, minimizing production downtime reduces maintenance costs.	A lack of specialized personnel with the necessary technical knowledge and skills to implement and manage XR solutions can hinder implementation and effective utilization.	Explore opportunities for partnerships and collaborations with technology providers, educational institutions, and industry leaders to drive innovation and implementation of XR technologies.	Evolving industry standards require continuous adaptation and compliance, which can lead to additional investments and updates. This can be resource-intensive and may slow down the implementation process.
Real-time data visualization allows ongoing analysis of process efficiency, enabling quick decision-making and process optimization.	Potential mental health issues for users, such as eye strain and dizziness from prolonged XR use, can affect employee well-being and productivity.	Identifying new areas where XR can add significant value expands its applications and benefits, driving further implementation and innovation.	The lack of standardization and common protocols among different XR platforms affects interoperability, making it challenging to integrate various systems and technologies seamlessly.
XR simulations and training reduce physical risks by better preparing employees for demanding conditions, potentially lowering workplace accidents and related costs.	Potential resistance from employees who may be reluctant to implement innovative technologies, and the need for change management strategies to facilitate smooth transitions.	New business models based on XR open innovative revenue streams and market opportunities, driving growth and diversification. Possibility of Influencing manufacturing standards	Dependence on foreign XR technology suppliers can increase costs and supply chain risks, particularly in times of geopolitical instability or trade restrictions.

Cont. Table 3.

Strengths	Weaknesses	Opportunities	Threats
The ability to conduct distributed teamwork in a virtual environment enhances collaboration and can lead to more efficient project management and execution.	Difficulty in providing a wide field of view (the range of the observable world at any given moment), currently AR/VR devices can provide 90°	Predictive maintenance XR tools combined with IoT data enable fault prediction and planned maintenance, reducing downtime and maintenance costs.	Increasing environmental regulations may impose stricter limits on emissions and carbon footprints, potentially restricting XR implementations due to their energy consumption and environmental impact.
Having a technological advantage over competitors can provide a significant market edge, attracting more clients and investment.	The need for continuous modernization due to rapid technological advancements may require frequent updates, increasing operational costs and potentially causing disruptions.	Integration of XR with big data and predictive analytics enhances the ability to predict failures and optimize production in real-time, improving operational efficiency.	The implementation of XR technologies introduces new cybersecurity threats, as these systems can be vulnerable to hacking and data breaches. Ensuring robust security measures is crucial to protect sensitive information.
Increased employee engagement using XR technologies can boost productivity and job satisfaction, leading to better overall performance.	Increasing complexity in managing XR systems necessitates collaboration between different platforms and communication protocols, which can complicate system management and maintenance.	XR-driven hazard simulations tailored to specific working conditions can improve safety training and preparedness, reducing workplace accidents.	Economic fluctuations can impact decisions to implement XR technology due to the high initial investment costs. Enterprises may delay or cancel XR projects during economic downturns.
Growing awareness that XR is a contemporary tool integrated into various industries facilitates its implementation and integration into existing workflows.	Limitations like compatibility and interoperability	The ability to create large-scale virtual programs expands training and operational capabilities, enhancing scalability and reach.	Currency fluctuations and raw material market instability can affect the costs of maintaining XR infrastructure, especially for imported components, leading to increased financial uncertainty.
XR proves to be a powerful tool for improving collaboration in supply chains and with customers, enhancing efficiency and customer satisfaction.		Long-term cost savings from reduced production defects can improve profitability and operational efficiency.	Negative public opinions about XR technologies can hinder their implementation.
		Development of more advanced and affordable XR devices increases accessibility and implementation, driving market growth.	Social resistance to XR and innovative technologies can slow down their implementation.
		Development of educational programs and specialized training in XR enhances workforce skills and readiness, support further implementation.	Health risks associated with prolonged use of XR, such as eye strain and dizziness, can affect employee well-being and productivity. Cybersickness.

Source: author's work based on literature review and analysis and technology reports.

Growing interest and technological advances in Extended Reality are expanding its applications across industries, particularly in enhancing collaboration, training, and manufacturing efficiency. XR training, particularly in augmented reality, reduces mental load compared to traditional methods (Doolani et al., 2020) enabling risk-free workplace scenario simulations that promote cost savings, improved occupational risk prevention, and enhanced decision-making (Ortega-Gras et al., 2023). XR also supports sustainable manufacturing by optimizing resource use and reducing material waste throughout the product lifecycle—from design to reuse (Chu, Pan, 2024).

XR applications improve coordination between remote teams, streamline project management, and enable faster feedback collection, cutting costs and reducing delays. Immersive virtual workspaces provide clearer, consistent project understanding, accelerating design processes (Cox, Theorem, 2024). In manufacturing, XR integrated with edge computing supports real-time data analysis and process optimization, reducing latency and increasing productivity. This technology also supports sustainable practices by minimizing the need for travel and enabling accurate simulations. It also facilitates real-time collaboration with remote teams and stakeholders, such as virtual factory tours that allow remote suppliers to understand spatial limitations and workflow constraints without the need for physical visits. This can lead to more efficient design adjustments and better alignment with production requirements. (Cox, Theorem, 2024) By the way, VR enables ergonomic workstation analysis by recording worker movements and integrating with Digital Human Modeling (DHM) tools to test various body types. A VR application in automotive cable assembly demonstrated its effectiveness in simulating manual tasks and identifying physical limitations (Reinhard et al., 2020). However, some challenges remain, including VR's technical limitations, high setup costs, and discrepancies between simulations and real-world conditions.

Despite its advantages, XR also comes with significant challenges, including high upfront costs, complex systems integration, compatibility issues and the need for specialized technical knowledge. The Future Today Institute report (Report Tech Trends, 2024) identifies eleven macro sources of disruption, including technology, media and telecommunications, demographics, environment, government, public health, education, geopolitics, infrastructure, economy, and wealth distribution that may impact implementation. XR technologies carry the risk of personal data leakage, which can be manipulated by enterprises or malicious actors for profit, which weakens trust and stifles innovation. (Report ... XRSI, 2021). Worker resistance, potential health effects such as eye strain, and privacy concerns – such as the collection of biometric data – are additional hurdles XR technology can inadvertently reveal the “biometric psychographics” of employees through eye tracking and video analysis, revealing emotional responses. When combined with brain-computer interface data and AI analysis, this can reveal sensitive personal data such as ethnicity and health, often beyond the user’s control. Additionally, the immersive nature of this technology may encourage users to share more personal information in virtual environments. (Vale, Berrick, 2023; Aziz, Morris, 2023; Raport: Human Capital

Trends 2024).Therefore, it is important to discuss opportunities and threats and develop common strategies to minimize the risk of abuse in the long term (Report ... XRSI, 2021; Report Tech Trends, 2024) Going further, technological challenges, such as display latency and limited field of view in AR/VR/MR devices, need to be addressed (Report Augmented and Virtual Reality Market..., 2024). Another challenge is motion sickness in VR, known as cybersickness, addressed through research into proprioception and sensory rebalancing. Studies show that music can alleviate symptoms, help reduce nausea and improve the comfort of VR. These findings could lead to more personalized and enjoyable virtual experiences.

Despite the barriers presented, the potential benefits of extended reality are more significant. It can improve safety, through virtual threat simulations and predictive maintenance capabilities, reducing downtime and repair costs when combined with IoT. Governments can promote XR implementation by lowering financial barriers and expanding XR reach. XR's integration with digital twins and AI is another promising area, as illustrated by Tomaszewska (2023), who points out that such synergies can improve operational efficiency and foster innovation within Industry 4.0. In addition, personalized XR-based training programs, supported by AI, offer customized learning solutions that address the needs of an aging workforce. The literature review shows that there is a need to combine digital twin, robotics and XR technologies to drive innovation, increase operational efficiency and support industrial collaboration within Industry 4.0. Research on these integrated technologies should also be continued to deepen their application and further development in industrial practice. (Feddoul et al. 2023).

However, the rapid evolution of XR standards and dependence on foreign suppliers introduces risks, requiring regular updates and compliance. Economic and political factors, such as market fluctuations and emissions regulations, may also influence the decisions of smaller enterprises facing high initial investments. While upfront costs remain high, the long-term financial benefits of XR implementation are becoming increasingly evident, and the development of more affordable XR devices continues.

4. Discussion

The Engineering.com report shows that most enterprises in the AEC industry are already using VR or plans to implement it within the next five years. The main driver of VR adoption is the return on investment – 49% of respondents indicated that VR helps detect design issues at earlier stages, resulting in cost savings. Other motivating factors include better remote collaboration (44%), reduced travel costs (35%), and sustainability (21%). VR enables more effective communication and reduces the need for rework through immersive design reviews and tools such as issue tracking and BIM data inspection. (Research Report: VR in AEC: Usage, Challenges and Opportunities, Autodesk, 2023) Companies like Walmart and Lufthansa have integrated VR to improve skills, from customer service to technical maintenance. VR offers a low-risk environment for hands-on learning, building muscle memory before real-world tasks. VR and AR are aiding prototyping and training processes in the automotive industry, helping enterprises like Ford and Jaguar Land Rover reduce costs and improve efficiency. Virtual prototyping and AR enable early error detection and improved product quality. BMW, meanwhile, has introduced XrealAir 2 AR glasses into its vehicles to display navigation and vehicle information, changing the way people interact with technology and ushering in a new era of smart glasses. In manufacturing, XR enables true-to-reality digital twins, optimizing complex systems and processes, such as automotive design and urban planning. Spanish startup OWO has unveiled a haptic vest that induces physical sensations, creating the foundation for deeply immersive tactile experiences in virtual worlds. (Report Tech Trends, 2024) French startup Weviz develops real-time 3D visualization software to support industrial design verification and reduce prototyping costs. (Manufacturing Trend Report, 2024)

Modelling and Simulation as a Service (MSaaS), in combination with Extended Reality (XR), is a transformative approach within Industry 4.0 that addresses contemporary challenges in design and manufacturing. Furthermore, XR generates new business value by streamlining the customer journey, optimizing employee performance and enabling the development of innovative content and services. (Mourtzis et al. 2024) Using XR technologies such as AR and VR, researchers can create immersive mock-ups to evaluate materials for reuse or recycling before deconstruction even begins. These simulations could provide information on the quality and reusability of materials, making it easier to determine which ones can be effectively recovered. XR-enabled feasibility studies can virtually simulate the deconstruction process, helping stakeholders identify challenges, refine techniques, and make informed decisions in advance. This forward-thinking approach not only improves decision making, but also drives more efficient and cost-effective practices in the deconstruction sector, setting a new standard for sustainable production and manufacturing. (Habeeb et al. 2024)

Major tech enterprises, including Microsoft, are integrating immersive collaboration features into their tools, like Microsoft Mesh in Teams, to enhance virtual meetings. This includes 3D avatars, spatial audio, and virtual environments, aiming to make remote collaboration more natural. Competing startups like Jugo and Frame also offer immersive meeting solutions, focusing on realism and customization. (Report Tech Trends, 2024) 5G's support for massive data transfer and real-time interactions offers new opportunities for XR applications, especially for remote collaboration and live events. This collaboration between XR and 5G is expected to drive growth and innovation. (Extended Reality Market Size, Share, Trends... 2023).

5. Summary

Extended Reality technologies, including virtual reality, augmented reality, and mixed reality, are rapidly gaining prominence across industrial sectors, becoming key trends in manufacturing (Manufacturing Trend Report, StartUs Insights, 2024). The successful integration of XR into industrial environments depends on a variety of factors, including social, technological, economic, and legal considerations. While younger workers' openness to innovative technologies and the shift toward remote work are accelerating XR implementation, challenges remain, such as generational gaps in technological acceptance and the high upfront costs of implementation. Additionally, XR's integration with another innovative technologies like the Internet of Things or Artificial Intelligence enables real-time monitoring, increasing production efficiency and reducing waste. However, the lack of standardized industry protocols, along with concerns around data privacy, cybersecurity, and regulatory compliance, continues to pose significant barriers. On the positive side, advancements in 5G technology and increased funding for Industry 4.0 initiatives are strengthening XR's potential. Nonetheless, the environmental impact of XR technologies, including high energy demands, necessitates a focus on sustainable practices. A supportive regulatory framework, global cooperation on standards, and government incentives are crucial to overcoming these challenges and driving broader XR adoption, enabling enterprises to gain a competitive edge and adapt to evolving organizational cultures.

To maximize XR's full potential, further research need in the following areas:

1. It would be worthwhile to expand research on XR interoperability and compliance standards, especially about integration with other industrial technologies such as digital twins and AI systems. Establishing unified standards could facilitate large-scale XR implementation and increase its overall effectiveness.
2. Given the high upfront costs and complexity of XR technologies, it is crucial to explore strategies to lower these financial barriers for smaller enterprises. Research could focus on models such as leasing, subscription-based systems, or government subsidies aimed at making XR solutions more accessible to SMEs that are constrained by financial constraints.
3. As XR adoption increases, developing tailored training programs that address the different learning preferences of different generations is essential to improving workforce acceptance. Structured change management processes can help overcome resistance and ensure a smoother transition to XR technologies.
4. XR technology has the potential to improve sustainable manufacturing practices. Future research should explore the use of XR simulations to assess the potential for material reuse and recycling in manufacturing processes.

Furthermore, future research should explore cross-sector collaborations for XR adoption, especially in areas where multiple industries could share resources, knowledge, and applications. For instance, XR technologies currently utilized in healthcare for training and maintenance could be adapted for similar uses in manufacturing. Additionally, the exchange of best practices between sectors like AEC and manufacturing could uncover synergies, particularly in design visualization, project management, and collaborative remote work. Collaborative XR initiatives across sectors could lead to the development of standardized frameworks, shared resources, and solutions for familiar challenges such as data security and system integration, thus making XR adoption more accessible and sustainable for all.

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