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REVIEW

A Systematic Review on Extended Reality Applications for Sustainable Manufacturing Across the Product Lifecycle

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Abstract

Extended reality (XR) has found successful applications in smart manufacturing as a human-machine interface in the context of Industry 4.0. Inspired by the evolving Industry 5.0, this paper investigates how XR has been utilized as a human-centric approach to realize environmentally sustainable manufacturing through a systematic literature review. Related studies are classified into the marketing, design, manufacturing, logistics, use, and reuse stages of a product life cycle. Our focus is to identify representative XR solutions in each stage and examine whether these solutions vary across the different stages. The findings derived reveal the level of maturity and potential research gaps in this field. This work provides insights for the manufacturing industry to effectively implement XR-assisted sustainable manufacturing.

Keywords Sustainable manufacturing · Industry 5.0 · Virtual reality · Augmented reality · Mixed reality · Extended reality

1 Introduction

Manufacturing systems that implement the concept of Industry 4.0 enable the flexible production of personalized products by making intelligent decisions through real-time communication and cooperation among all entities within the system. The essence of Industry 4.0 is to realize cyber-physical systems (CPS) that seamlessly integrate real-world objects and cyberspace to provide adaptability and autonomy. Industry 5.0 results from the European Commission's consensus on the need to better integrate social and environmental priorities into technological innovation [1]. Industry 5.0 offers a different perspective that emphasizes the significance of creating long-term value for humanity while remaining within the boundaries of the planet [2]. It complements the existing Industry 4.0 paradigm by prioritizing engineering research to facilitate the transition towards a sustainable, human-centric, and resilient global industry [3], as shown in Fig. 1.

Nine key technologies have been identified to enable Industry 4.0, including big data, autonomous robots, simulation, horizontal and vertical system integration, industrial Internet of Things, cybersecurity, cloud computing, additive manufacturing, and augmented reality (AR). Of the list above, only AR is a human-centric technology designed specifically for end users, which allows for real-time user interaction with real-world or virtual contents through a variety of sensory modalities. While artificial intelligence (AI) can enable manufacturing systems to operate with a high degree of autonomy and intelligence, there are certain tasks that remain infeasible or impossible to accomplish without human intervention. As a result, AR has found increasing applications in manufacturing systems, particularly to assist manual operations of maintenance, assembly/disassembly, inspection, and inventory management by enhancing the user's situation awareness [4]. With this potential, AR could play a critical role in the era of Industry 5.0 to further extend CPS into human-cyber-physical systems (HCPS). It provides decision support for different stakeholders while bringing data, available knowledge, and the current real-world situation together through context-specific visualization [5].

Extended reality (XR) is an umbrella terminology that includes virtual reality (VR), augmented reality, and mixed reality (MR). Figure 2 shows the virtuality-reality continuum that incrementally transforms from a virtual world to a real environment [6]. XR aims to create an immersive user experience by integrating various sensory cues that simulate the real world along the virtuality-reality continuum. In this

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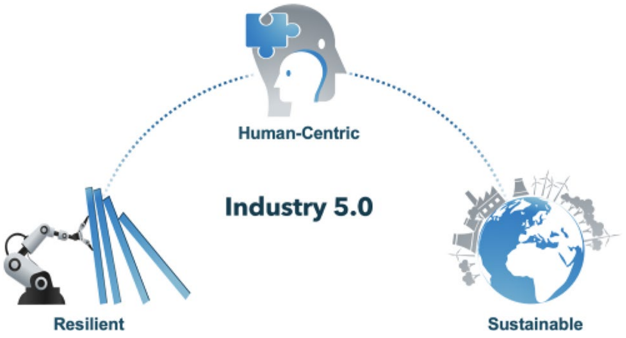


Fig. 1 Core values of Industry 5.0 [3]

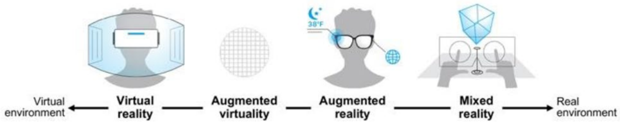


Fig. 2 The virtuality-reality continuum for XR technologies

continuum, VR allows users to interact with a computer-generated 3D virtual environment in an immersive manner. AR superimposes virtual content onto real-world scenes to enhance user's perception and situation awareness of their environment. MR is an evolution of AR that enables users to have real-time interaction and communication with both real and virtual elements. Regardless of the position in the virtuality-reality continuum, all XR technologies are designed to fulfill user's needs, namely human-centric approaches. This feature conforms well to the human-centric core value in Industry 5.0. AR/MR technology is expected to have great potential in the application of life cycle engineering (LCE) in industry by facilitating data visualization and information communication [7]. As an extension, it is necessary to understand the state-of-the-art of XR solutions for sustainable manufacturing. The paper conducts a systematic literature review (SLR) and classifies the collected studies according to a framework that spans the product life cycle. Our goal is to provide an overall analysis of the potential of XR and to identify research gaps in environmentally sustainable manufacturing. This can be achieved by answering the following two research questions.

1. What are representative XR solutions for each stage in the product life cycle?
2. Do XR solutions driven by environmentally sustainability vary across different stages of the product life cycle?

The paper is organized as follows. Section 2 describes the literature search methodology used in this work. Section 3 classifies the retrieved literature using the proposed framework and compares the results across different lifecycle stages. Section 4 summarizes representative works in each stage. Section 5 reports the findings derived in previous sections by answering the two research questions. The last section presents concluding remarks for this paper, including discussions on research gaps and future research areas.

2 Methodology of Systematic Literature Review

A systematic literature review has been conducted to investigate the recent advancements of XR applications developed for sustainable manufacturing. Google Scholar was used as a primary data source to identify publications with scientific contributions in this field. The search period was limited to publications after 2017. Four pairs of keywords were initially used to start the search: "Virtual Reality" OR "Augmented Reality" OR "Mixed Reality" OR "Extended Reality" AND "Sustainable Manufacturing". The publications retrieved were screened through reading for further analysis. Most of the studies excluded during the screening process addressed sustainability issues in non-manufacturing sectors, such as the construction industry [8], livelihood facilities, and societal organizations. These topics are not the focus of this paper.

The basic objectives of sustainable manufacturing are to reduce the consumption of non-renewable resources, minimize waste, and create healthy work environments during the manufacturing process. Similar to other manufacturing challenges, achieving these objectives requires specific actions to be taken at each phase of a product's life cycle. These actions may also involve different stakeholders, limitations, and solutions facilitated by XR. Classifying studies on sustainable manufacturing based on the product lifecycle stage can provide insights that are essential to answer the two research questions. We propose to analyze the studies retrieved using a systematic approach that will allow us to identify patterns in how XR enables sustainable manufacturing across various stages, including marketing, design, manufacturing, logistics, use, and reuse/recycle. To enhance environmental sustainability, an XR solution should include key elements such as an actioner, an influenced entity, instructive information, and a well-defined sustainability

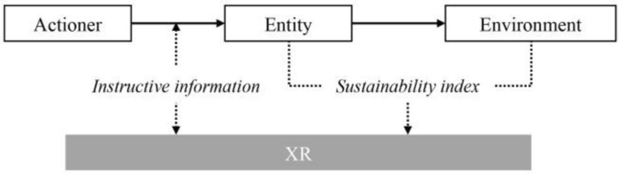


Fig. 3 Key elements of XR applications in sustainable manufacturing

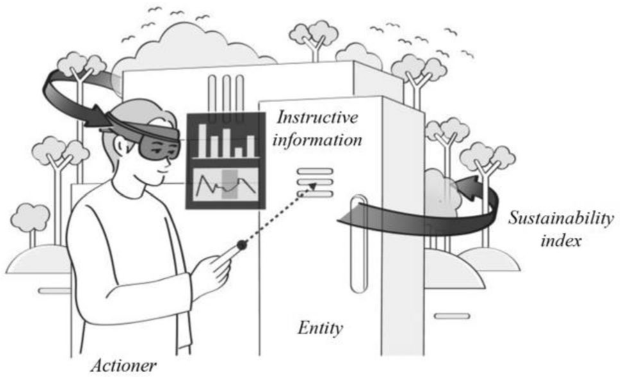


Fig. 4 A schematic of XR solutions in sustainable manufacturing

index, as shown in Fig. 3. Figure 4 shows a schematic in which the actioner changes the behavior of the entity based on the instructive information presented in XR to improve the sustainability index. The key elements involved in XR solutions may vary depending on the lifecycle stage in which they are implemented.

3 Classification of Literature

The publications retrieved from the literature search were classified into the six stages of a product life cycle. We conducted a thorough reading of the papers and systematically analyzed individual research ideas using the approach outlined in Fig. 3. Table 1 lists the classification result by the reference number. The breakdown of these 47 papers is as follows: marketing (14), design (4), manufacturing (7), logistics (8), use (3), and reuse/recycle (12). The marketing and reuse/recycle stages have received greater research attention compared to the other stages, while fewer studies have focused on design and product in use. Table 1 also shows the specific XR technology used in each study. Since most studies do not differentiate between AR and MR in their applications, both terms are interchangeable in the classification. The result indicates that, except for the marketing stage, AR has been used more frequently than VR in sustainable manufacturing. The most common device used in the XR applications under investigation are handheld devices (HHDs), such as smartphones and tablets. HMD devices, such as goggles and smart glasses, have also gained popularity recently mainly because they free the user's hands. In contrast, monitor and 3D projector have been less commonly employed in the retrieved studies. Table 1 further categorizes the related studies by the type of work. Approximately one quarter of the studies belong to the conceptual framework category, while the remaining three quarters have developed XR solutions either as software or through the integration of software and hardware.

We attempted to analyze the XR applications developed for each life cycle stage using the schematic shown in Fig. 4. Our goal was to identify common patterns, if they exist, that consist of an actor, an entity to be affected, and a sustainability index for assessment. Table 2 summarizes the patterns identified from the studies classified according to the life cycle stage. The actor is typically the main stakeholder in a life cycle stage. XR applications are developed to reduce the environmental impact by affecting the human behavior/thought in the marketing stage, or by adjusting products, machines, and facilities in manufacturing during the other stages. The sustainability index that guides XR applications varies across different life cycle stages. No singular predominant index has been identified for each stage.

4 Representative Works in Product Lifecycles

4.1 Marketing

Consumer habits, lifestyle choices, and engagement play a crucial role in achieving sustainable development [9].

Table 1 Classification of studies by specific XR technologies, deployment devices, and types of work

Product life cycle	References	XR technology		Deployment device				Type of study	
		AR	VR	HMD	HHD	Monitor	3D projector	Framework	Application
Marketing	[11–24]	(11–13, 18, 20-23)	(14–17, 19, 24)	(18, 21)	(11–13, 20–23)	N/A	(14, 15)	(16, 17, 19, 24)	(11–15, 18, 20–23)
Design	[27–30]	(28–30)	(27)	(29, 30)	(28)	N/A	N/A	(27)	(28–30)
Manufacturing	[32–38]	(32–36)	(37, 38)	N/A	(32–36)	N/A	[38]	N/A	(32–36, 38)
Logistics	[40–47]	(40–44, 46, 47)	(45)	(41, 43, 45, 46)	(40)	N/A	N/A	(42, 44, 47)	(40, 41, 43, 45, 46)
Use	[50–52]	(50, 52)	N/A	(50)	(52)	N/A	N/A	(51)	(50, 52)
Reuse/recycle	[54–64, 66]	(54–56, 58–64, 66)	(57)	(59, 63)	(58, 60–62, 64)	(54, 55, 57)	N/A	(56, 66)	(54, 55, 57–64)

Table 2 Analysis of XR applications by the proposed schematic

Product life cycle	Actioner	Entity	Sustainability index
Marketing	Educator/advocator	User/consumer	Sustainability awareness (11)
			Circular economy knowledge (12, 13)
			Sustainable behavior acceptance (16, 20, 22)
Design	Designer	Product	Material diversity (25)
			Material recyclability (25)
			Thermal environmental map (29)
			LCA data interactivity (30)
Manufacturing	Operator	Machine	Energy consumption (32–35, 38)
			Manufacturing cost (36)
			Greenhouse gas emission (36)
Logistics	Operator	Logistic facility	Material handling efficiency (40)
			Order picking error rate (41)
			Order picking (43)
			CO_2 emission (44)
Use	Operator	Machine	Corrosion rate (50)
			Machine residual lifetime (50)
			Machine health index (51)
			Maintenance workforce condition (51)
Reuse/recycle	Operator	Product	Material recyclability (55, 58)
			Disassembly efficiency (54, 55, 60)
			Components reuse rate (58)

Raising people's awareness of the potential impact of manufacturing activities on the environment may be an important first step. VR/AR technologies are expected to facilitate modern marketing practices due to their widespread use and superior extensibility [10]. Bekaroo et al. [11] implemented an AR mobile application that provides real-time information about the energy consumption of electronic devices being used at home and offices. The study found a positive correlation between the use of the app and the willingness to reduce energy consumption of electronic devices. Lönn [12] developed an AR smartphone application to educate users about the recyclability of engineering products. The evaluation of the prototype indicated that AR is a useful tool to supplement other sources of information related to the circular economy (CE). Katika et al. [13] presented a novel AR engagement tool and the results of two studies evaluating the reliability and validity of this tool in engagement practices. They confirmed that AR can increase social inclusion and community cohesion by raising public awareness of the benefits of the CE.

VR technologies were also frequently used as an educational tool to prepare future engineers for sustainable manufacturing [14–19]. Damian et al. [14] incorporated recycling requirements into the product design stage, implemented them in a 3D environment, and utilized immersive VR to enhance the training of designers. Salah et al. [15] proposed to utilize VR in product manufacturing to familiarize students with the concept of Industry 4.0, specifically the reconfigurable manufacturing system. Scurati et al. [16] described a system framework for designing VR experiences that support behavior change towards more sustainable choices and consumer habits. The framework allowed designers to explore a variety of ideal options while creating customized solutions. VR has been used to reduce the time required to recognize and understand energy information on the shop floor [17]. Visualization based on modeling the processes, machines, and production lines, as well as their interdependencies, could be an effective tool in assisting the evaluation of energy demands in a manufacturing facility. Czarski et al. [18] integrated learning content on HVAC (Heating, Ventilation, and Air Conditioning) systems into a demonstration factory using MR to provide engineers with a better understanding of energy management and system optimization. Krupnova et al. [19] developed VR applications to educate students on sustainability in the context of Industry 4.0. The advantages and disadvantages of utilizing VR in student training were compared to traditional methods such as lectures and papers reading.

MR technologies have been applied to promote sustainable consumption behaviors through training games, recommendation agents, and sustainability dashboards [20–22]. Fraternali and Gonzalez [20] developed an AR game to promote the concept of energy efficiency and sustainable consumption among children and their families. Viklund and Sjölander [21] evaluated the usability of a sustainability dashboard solution that presents sustainability information

Fig. 5 HMD based AR sustainability dashboard [20]

on a monitor, mobile device, and an AR HMD, as shown in Fig. 5. The evaluation result indicated a preference of the HMD based solution. Joerss et al. [22] implemented AR-based recommendation agents (AR-RAs) in retail stores to encourage consumers to consider sustainability when making purchasing decisions. Serious games implemented by AR and VR have been developed to raise awareness about climate change and sustainability [23, 24].

4.2 Design

Eco-design considers the environmental impacts caused by the entire product life cycle in the early design stage. There are three levels of motivation in implementing eco-design [25]. The factors driving the adoption of green practices at the first level include competitive advantage and mandatory legislation. At the second level, the emergence of new customer preferences for sustainability stimulates innovation of new products. The third level involves communication and integration of stakeholder values into the design stage. VR/AR have been utilized in co-design and co-creative design for consumer products that are environmentally friendly [26].

A case study on a hammer drill [27] showed how VR technology can be used to evaluate and optimize the product's design, operation, and recycling potential at the design stage. VR was used to simulate the disassembly sequence of a device, analyze the degree of product recycling, and explore the potential for creating new product variants for better end-of-use outcomes. Zheng et al. [28] proposed a data-driven co-creation platform for designing environmentally friendly products. The user experience of the products can be visualized in AR, providing valuable feedback to manufacturers for design improvements through a cloud-based platform.

Data visualization is a primary advantage of XR technology, which allows for the design of future products and their life cycles in a prospective manner. The efficiency of indoor thermal design is often hindered by constraints in the design process and the complexity associated with interpreting simulation outcomes. To address this issue, Fukuda et al. [29] proposed combining AR and computational fluid dynamics (CFD) to create intuitive visual representations of CFD findings in a real environment. This approach enabled users to actively evaluate the impact of various design options on the thermal atmosphere shown in Fig. 6. The multidimensional outcomes and intricate interconnections among influencing factors can make Life Cycle Assessment (LCA) difficult to comprehend and interpret. Kaluza et al. [30] developed a decision-making tool based on MR to aid the implementation of life cycle engineering in the automotive industry. This tool aimed to improve the interactivity and understanding of LCA findings.

4.3 Manufacturing

A manufacturing system typically consists of essential elements such as materials, machines, processes, and human resources, which are interconnected through a variety of energy and resource flows. The system converts these elements into valuable products, but also generates various types of waste and emissions as byproducts. In this regard, efforts to achieve environmentally sustainable manufacturing can be classified into three categories: improving energy efficiency, enhancing material efficiency and circularity, and adopting more sustainable energy and material sources [31].

The integration of AR and VR technologies with IoT to monitor and visualize real-time energy consumption has been an effective approach on the shop floor [33]. Engineers can make more informed decisions regarding energy management when they have access to real-time operational data. Amici et al. [32] proposed an Industrial Augmented Reality (IAR) system that measures and displays electrical energy consumption of equipment installed in an IoT enabled production line as shown in Fig. 7. Displaying real-time electrical current and voltage of individual equipment enables production managers to identify potential power issues, save energy, and reduce operating costs. Ho and Chui [34]

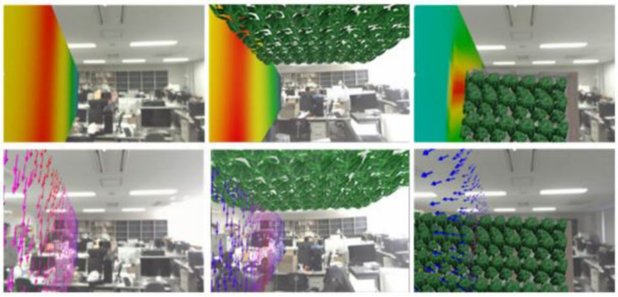


Fig. 6 AR assisted thermal visualization renovation design [29]

Fig. 7 IAR application for energy monitoring [32]

developed an AR application that displays an overall view of the energy consumption in a work cell and the individual energy usage of each equipment comprising the cell. Users can remotely identify equipment with constant high consumption rates and quickly make adjustments to reduce energy usage. Naret et al. [35] proposed a virtual display solution for monitoring the power consumption of electrical equipment by integrating AR, IoT, and wireless network. IoT-compatible sensors collected the electrical consumption of each equipment and transmitted the data through WiFi for remote display on mobile devices in the form of a dashboard. The proposed solution reduced the need for manual scanning and recording of energy usage on site.

Yi et al. [36] proposed an approach based on cumulated cylinders to approximate the geometry of the component being constructed in additive manufacturing. As shown in Fig. 8, four process indicators (electricity use, manufacturing cost, greenhouse gas emission, and energy consumption) were modeled and integrated in an AR-based digital twin. The feasibility and performance of the digital twin were demonstrated through printing test components. Checa et al. [37] combined experimental tests, machine-learning modelling, and VR visualization to improve the selection of cutting tools in machining operations and for training engineering students. Three VR-based energy visualization methods: 2D Billboard, 3D Sankey diagram, and a 3D particle flow technique, were cross-compared with energy values determined from real measurements on the actual machine tool [38]. A short user survey was conducted to select the best VR-based energy visualization technique to improve energy efficiency in machine tool design and manufacturing.

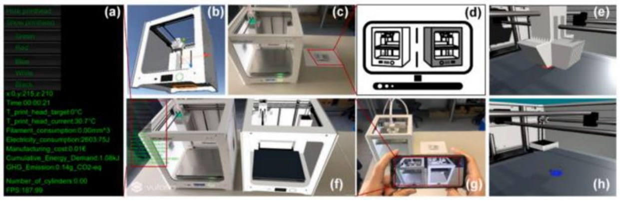


Fig. 8 AR based digital twin for additive manufacturing [36]

4.4 Logistics

AR has been recognized as a key enabling technology in Logistics 4.0 to improve logistics and warehouse operations by reducing labor costs and enhancing efficiency in picking, shipping, and inventory planning [39]. Environmentally sustainable manufacturing directly benefits from reducing the energy required for material flow [40–44].

Sidiropoulos et al. [40] developed a mobile AR application for indoor guidance that facilitates time-critical processes and material handling inside a warehouse (see Fig. 9). Integrated with a 3D floor plan of the warehouse facility, the application identifies the best route and guides operators to move accordingly within the facility. A case study was conducted on order picking at a distribution center of a major telecommunications service provider using an AR application deployed in smart glasses [41]. The study concluded that the app can provide effective solutions for order picking routing and scheduling, especially in situations where operational conditions change dynamically during existing routes. The AR application resulted in faster completion time and fewer errors compared to the traditional paper-based system. Jumahat et al. [42] reviewed 36 cases of AR pick-by-vision applications in warehouse management systems. They focused on the potential benefits of these applications in logistics and analyzed their technical characteristics. Based on the analysis results, the potential benefits primarily revolve around improving productivity, operational efficiency, and enhancing user comfort and satisfaction. Figure 10 shows an AR application in Microsoft HoloLens that assists warehouse operators in optimizing the location of products by visualizing turnover rates and relocation of products [43]. The test results confirmed that that

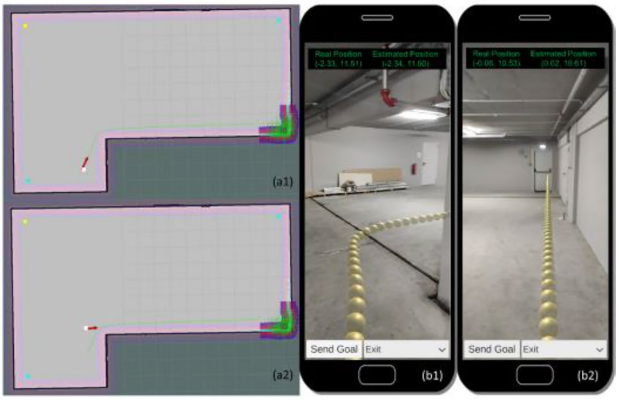


Fig. 9 AR indoor guidance for warehouse logistics [40]

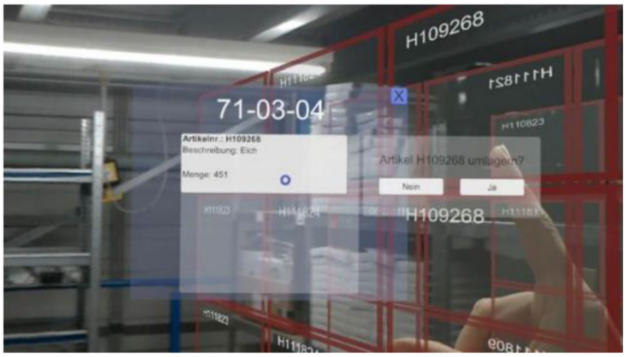


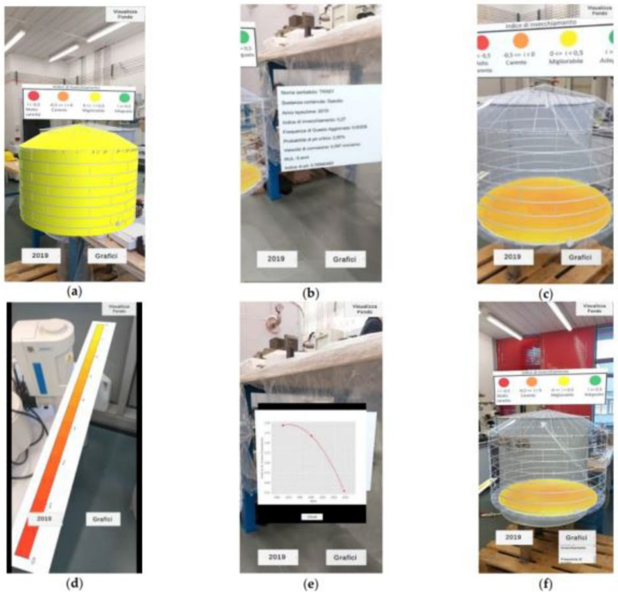
Fig. 10 AR warehouse visualization for storage relocation [43]

the app can be an effective solution for managing warehouse operations with dynamic work conditions during the picker's route. VR has been applied to support communication for design review between a technology center in Sweden and a manufacturing site in China, thus reducing travel frequencies and minimizing CO2 emissions [45]. This reduction was verified through feedback from focus group discussion and questionnaire.

Although the above studies have demonstrated the applicability of XR in logistics, there may still be more areas to explore. Stoltz et al. [46] conducted a series of practitioner interviews and hands-on experiments using Google Glass with warehouse managers, solution providers, and logistics experts. Their goal was to identify the opportunities that arise from using AR in warehouses and the barriers to its industrial adoption. Their findings indicated that user-friendly interface design, wearing comfort, broad field of view, image scanning, and ease of customized programming require further improvement. Ginters [47] presented a conceptual framework for the use of AR-assisted logistics operations, emphasizing the need for standardized, modular, and open design. The framework consists of four levels: AR hardware (L1), assistive technologies (L2), object identification (L3), and logistics scenarios implementation (L4). They emphasized the need to address software and hardware compatibility issues and ensure the self-sufficiency of AR solutions.

4.5 Use

Maintenance is an indispensable task in most production systems to ensure that machines are always working properly. Malfunctioning machines can increase energy consumption and generate hazardous substances during manufacturing processes. Eliminating unscheduled downtimes and timely monitoring of equipment health are crucial for achieving sustainable production. Maintenance is still a labor-intensive task and prone to human errors in most shop floors. Previous studies [48, 49] have systematically reviewed how AR technology can assist users in improving their performance during maintenance of manufacturing equipment. This current study is specifically focused on XR-assisted maintenance activities with a direct environmental impact.



(a) (b) (c)

(d) (e) (f)

Fig. 11 AR visualization of chemical container corrosion data [50]

Figure 11 shows the virtual sensor system that displays prognostic estimates in AR for equipment in the chemical and process industry, including corrosion rate, probability of critical pit, corrosion evolution, and residual lifetime [50]. The system helped plant inspectors understand the aging level of the equipment, thus allowing effective maintenance and reduction of toxic substances caused by aging. Singh et al. [51] proposed a conceptual framework supported by MR technologies for operation of hydropower plants. The framework provides on-site inspectors with key variables, such as machine health, maintenance workforce, and decision-making support, that can enhance power generation efficiency. Angelopoulos and Mourtzis [52] developed an Intelligent Product Service System (IPSS) for adaptive maintenance of engineered-to-order industrial equipment in manufacturing industry. The system provides maintenance personnel interactive AR instructions for assembly, disassembly, and inspection tests on manufacturing equipment for energy reduction and improving on-time delivery rates.

4.6 Reuse/Recycle

Product disassembly planning is critical for reducing environmental impact at a product's end-of-life by enabling component and material recovery and waste reduction. Disassembly is also necessary for equipment maintenance and repair operations to ensure proper function. Recent surveys on disassembly planning have concluded that disassembly is a labor-intensive task and a perfect mathematical solution may not be feasible in practice [53]. Traditionally, operators perform disassembly tasks based on prior experience, paper, or video-based instructions, which may be error-prone and inefficient. AR works as an effective interface that facilitates manual disassembly by incorporating computational intelligence in real-time.

An AR-supported product disassembly planning system (ARDIS) determines the optimal disassembly steps by metaheuristic algorithms and creates AR instructions on-the-fly [54]. A pre-defined template was designed to connect each step and improve planners' understanding. Frizziero et al. [55] proposed a methodology for disassembly sequence planning that compares feasible disassembly sequences using genetic algorithms formulated as a state space search problem. AR scenes were created to visually validate the optimal disassembly process (see Fig. 12). Quesada-Díaz and Syberfeldt [56] integrated AR with product identifiers and lifecycle management for secure and efficient data management, and operator support in disassembly and inspection processes. Pascault et al. [57] developed a method to optimize the preparation time of VR simulations by generating and modeling assembly semantic meaning from product assembly features. The method extracted and translated assembly semantic features from CAD models by identifying semantic rules through a disassembly process. Mircheski and Rizov [58] proposed an AR-based model for nondestructive disassembly of end-of-life electromechanical products. The model incorporated RFID technology for product and part tracking during the disassembly process. The proposed model aimed to improve the recovery of materials, enable functional component reuse, and minimize environmental impact. A conceptual framework supported by an online network and AR technology was developed to assist the decision-making process for retrofitting and recycling machinery [59]. The framework allowed extending the lifespan of components by facilitating retrofitting of existing machinery with new features and enabling recycling of components from machines no longer operational.

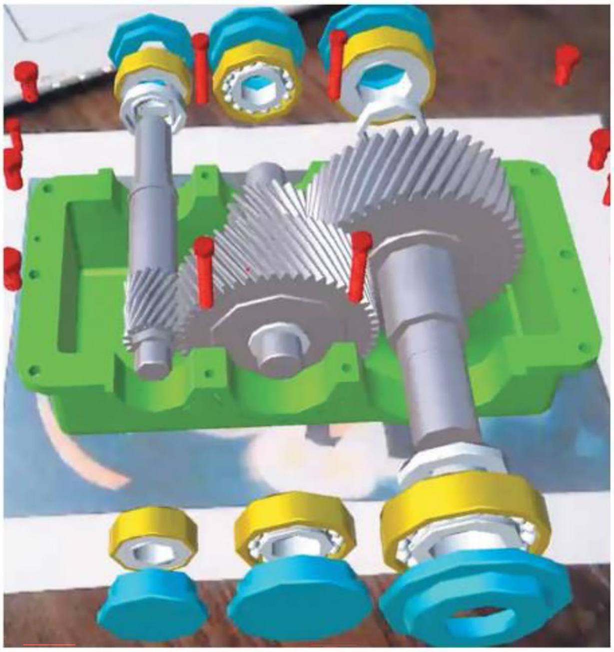


Fig. 12 AR-supported disassembly sequence planning [55]

Design for Disassembly (DfD) is a recurring technique employed in several studies to optimize disassembly processes, reduce waste, and enhance sustainability. Ritucci et al. [60] applied four metaheuristic methods to find the optimal disassembly sequence, thus minimizing time and cost while preventing damage to other mechanical parts. The disassembly sequence generated by the methods instructed operators to implement the concept of DfD, bringing substantial benefits to the practice. The Disassembly Geometry Contacting Graph (DGCG) technique was incorporated into disassembly sequence planning to find optimal disassembly sequences of a mechanical valve [64]. The comparison of different feasible sequences was based on the disassembly time required. An AR application was implemented to simulate a practical evaluation. The remanufacturing process typically includes processes such as disassembly, cleaning, inspection, repairing, or replacing the defective parts, reassembly, and testing [65]. A study conducted by [66] evaluated the sustainable performance of the engine remanufacturing process at Volvo Group Truck Operation using both quantitative and qualitative approaches. The study also identified the environmental benefits of implementing AR on the shop floor, which can help the company evaluate its sustainable performance and identify the contribution of the remanufacturing process towards sustainability. Yang et al. [67] categorized the enabling features and expected functionalities required for XR–lean Disassembly Sequence Planning (DSP) for end-of-life (EoL) aircraft parts, and proposes a new concept of "Smart Disassembly Sequence Planning (SDSP)" as a research agenda that integrates XR and lean into DSP.

5 Findings and Discussion

This section discusses the findings derived from analyzing the studies mentioned in previous sections. These findings may offer potential answers to the research questions raised at the beginning. Research on XR-assisted sustainable manufacturing is in the preliminary stage. This conclusion is supported by the fact that the publications listed in Table 1 contain more conference articles than refereed journal papers. Environmental sustainability has not been a primary focus in the XR applications developed for smart manufacturing thus far. It is necessary for humans to play a significant role in any operations or decision-making to be facilitated by XR. This condition applies to manual manufacturing operations, including calibration, inspection, and disassembly [4, 68]. Performance assessment in these operations typically focuses on productivity, quality, and safety, rather than sustainability issues. Understanding how human–machine interactions influence environmental sustainability in manufacturing is lacking and thus requires further analysis. On the other hand, there have been more works involving XR technologies to enhance sustainability in other sectors such as the HVAC, building, and construction industries [69, 70].

Based on the analysis of reviewed papers, the marketing and recycle/reuse stages have received the most attention in terms of the number of publications. Both VR and AR have been commonly used as a marketing tool by companies to draw people's attention to the environmental impact induced during a product life cycle. The focus of the recycle/reuse stage has been on disassembly sequence planning and on-site execution supported by AR. VR has also been used for interactive training in manual disassembly and repair operations. A common approach in the manufacturing stage is to monitor and visualize machine energy use on the shop floor. Instructions are then given to operators through AR interfaces to make necessary adjustments. Fewer studies have focused on improving sustainability during the design and product in-use stages, particularly when excluding XR applications in manual maintenance.

The product lifecycle can be viewed as a progression of information from a fuzzy front-end to specific product embodiment that enables a reliable production process [71]. An interesting finding from the reviewed literature is the correlation between the product lifecycle and the virtuality-reality continuum. VR is mostly utilized in the initial stages such as marketing and design, where the product form is still abstract. It is used as a visualization technology to show potential environmental impact at these stages. In contrast, AR/MR applications are mainly adopted for manufacturing, logistics, use, and recycling/reuse, after the physical form of the product has been established. As shown in Fig. 13, the level of reality in an XR solution should match appropriately with the corresponding stage of the product lifecycle, namely the level of reality is lower for earlier activities and higher for later ones. This correlation could serve as a useful guideline when developing XR tools for sustainable manufacturing.

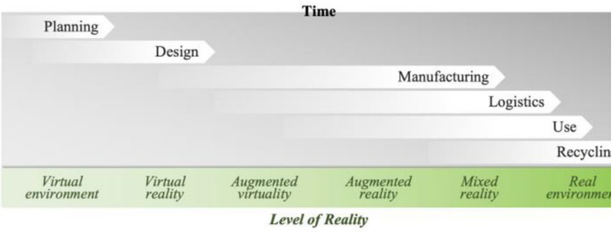


Fig. 13 Level of reality in XR corresponds to different stages of the product lifecycle

6 Conclusion

Industrial activities account for a significant share of global energy consumption and CO2 emissions. Most companies are thus faced with the challenge of reducing environmental impacts from their manufacturing activities while maintaining profitability and productivity levels. Recent advancements in information and communication technologies have facilitated smart manufacturing to attain product mass customization in the era of Industry 4.0. These technologies are anticipated to provide effective solutions for the implementation of sustainable manufacturing practices. Extended reality serves as a ubiquitous interface that enhances real-time interaction and communication between humans and both virtual and real environments. XR systems have been successfully implemented in manufacturing to enhance human situation awareness and decision-making in manual operations, thus improving the work performance in terms of efficiency and quality. This study conducted a systematic review of recent studies that specifically focused on XR applications developed for sustainable manufacturing. The publications obtained from the review were categorized based on the different stages of a product cycle. Each study was analyzed to determine the research type, specific XR technology, and deployment device used. The analysis results yielded several important findings.

A greater number of XR solutions have been developed for the marketing and reuse/recycle stages, whereas fewer studies have focused on design the product in use. Handheld devices like smartphones and tablets were the most commonly used in the reviewed studies, followed by HMD devices. We have proposed a schematic that comprises an actioner, an influenced entity, instructive information, and a well-defined sustainability index to examine and facilitate the design of XR solutions. The specific elements of the schematic may vary with the lifecycle stage in which the solution is implemented. The enabling XR technology within the virtuality-reality continuum should be appropriately matched with the changing levels of reality as a product lifecycle progresses. Finally, XR applications for sustainable manufacturing are still in the preliminary stage, unlike the construction and architecture industry where they have been more extensively developed. It is worth noting that environmental sustainability has not been the primary focus in XR-assisted smart manufacturing, compared to other priorities such as work efficiency and quality. To fully exploit the potential of XR in sustainable manufacturing, it is essential to understand and characterize the impact of human–machine interactions on environmental sustainability across different product lifecycle activities, particularly for the design and product-in-use stages. This work is one of the earliest reviews on XR studies specifically focused on environmental sustainability in smart manufacturing. The findings and discussions presented here can serve as guidelines for the implementation of practical XR tools that align with the concept of Industry 5.0.

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Declarations

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