A Survey on Extended Reality Technologies for Industrial Maintenance

Mouad Danane, Abdelmajid El Ouadi, Youssef Rochdi
National School of Applied Sciences, Ibn Tofail University, Kenitra, Morocco

***Abstract*—Industrial maintenance increasingly relies on extended reality (XR) technologies, yet comprehensive analysis comparing AR, VR, and MR implementations with human-centric evaluation remains limited. This systematic literature review employs the PRISMA methodology to analyze 95 primary studies (2014–2025) that investigate implementation patterns, benefits, challenges, and evaluation criteria across XR modalities. AR dominates operational guidance (71.6%), VR prevails in training (38.9%), and MR enables collaborative maintenance (6.3%). Temporal analysis reveals three evolutionary phases: basic visualization (2014–2017), cognitive enhancement (2018–2021), and AI-integrated adaptive systems (2022–2025), mirroring the transition from Maintenance 4.0 to 5.0. Demonstrated benefits include 38% task completion time reductions and 92.4% error decreases. Human-centric factors appear in 44.2% of studies overall, with temporal analysis showing a progressive increase from approximately 25% in 2014–2017 to 58% in 2022–2025, substantiating a paradigm shift toward prioritizing cognitive support and user experience. Two novel frameworks advance theoretical understanding: an Evaluation Framework that expresses effectiveness as a function of technology, task complexity, and human factors; and a Technology-Task-Context Alignment Model that prescribes optimal XR-maintenance pairings. Critical gaps include the need for longitudinal field studies, standardized evaluation protocols, and economic analyses.**

***Keywords*—Industrial maintenance; maintenance 5.0; extended reality; augmented reality; virtual reality; mixed reality; human-centric design; artificial intelligence; systematic literature review**

I. Introduction

Manufacturing industries worldwide face mounting pressure to optimize operational efficiency while managing increasingly complex equipment and production systems [88]. Industrial maintenance, encompassing inspection, repair, diagnosis, and preventive activities, is essential for maintaining uninterrupted production, reliable equipment performance, and safe working conditions [89]. The advent of Industry 4.0, marked by the convergence of digital-physical systems, IoT technologies, AI, and sophisticated data analytics, has fundamentally transformed maintenance paradigms [90]. Despite these technological advances, human operators remain essential in overseeing, supervising, and servicing automated infrastructure, tackling issues beyond the scope of automation capabilities [91]. This industrial evolution seeks to augment human operator performance and minimize human error through intelligent, human-centered systems [92].

Extended Reality (XR)—which includes Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR)—has become a powerful enabler for industrial maintenance [86]. These immersive technologies offer distinct capabilities: AR overlays digital information onto physical environments, enabling real-time guidance during maintenance operations; VR creates fully immersive virtual environments for risk-free training and simulation; MR blends digital and physical elements to facilitate collaborative problem-solving [93]. The convergence of XR with advanced industrial technologies, including IoT sensors, digital twins, and AI-driven analytics, creates unprecedented opportunities to improve maintenance efficiency, training effectiveness, and knowledge transfer [94]. The demonstrated benefits include substantial reductions in task completion time, significant decreases in failure rates, enhanced mental support for complex procedures, and improved knowledge retention during training [95].

Despite substantial research attention, critical gaps persist in our understanding of XR application in industrial maintenance. Existing reviews have primarily focused on individual XR modalities, without adopting comprehensive approaches that compare AR, VR, and MR. In addition, limited attention has been paid to human-centric design principles and systematic evaluation methodologies, which are increasingly recognized as critical to successful implementation. The rapid technological evolution—particularly post-2020 advances in hardware capabilities, AI integration, and software platforms—necessitates updated analysis reflecting current state-of-the-art systems. Finally, the emerging Maintenance 5.0 framework, which emphasizes human-AI collaboration and sustainable practices, requires examination of how XR technologies facilitate this paradigm shift.

Several systematic reviews have previously examined aspects of this domain. Palmarini et al. [83] conducted an early review focused exclusively on AR in maintenance, identifying fragmented solutions and hardware limitations. Guo et al. [84] reviewed VR applications across product lifecycles. More recently, Wang et al. [82] examined XR in product assembly, and Alam et al. [86] analyzed XR challenges in Industry 4.0 contexts. However, none of these reviews comprehensively compare all three XR modalities (AR, VR, and MR) while simultaneously addressing human-centric design factors, evaluation methodologies, and the emerging Maintenance 5.0 framework. This gap motivates the present study.

This systematic review fills these research voids through an in-depth examination of XR technologies in industrial maintenance through examination of 95 primary studies published between 2014 and 2025. The review adopts a holistic approach that encompasses AR, VR, and MR technologies, while emphasizing human-centric design factors aligned with the Maintenance 5.0 principles. This work offers multiple novel contributions that advance the current literature. First, it provides updated empirical evidence of XR adoption patterns, technological trends, and implementation outcomes reflecting recent advances. Second, it systematically analyzes evaluation methodologies employed across studies, identifying relationships between technology characteristics, task complexity, and appropriate assessment criteria. Third, it examines human-centric enhancement strategies, documenting how XR technologies address cognitive load, ergonomics, adaptability, and user experience. Fourth, it develops theoretical frameworks that advance understanding of XR effectiveness in maintenance contexts.

To achieve a comprehensive analysis, this review addresses five research questions: XR implementation patterns, benefits and potential, challenges and prospects, human-centric enhancements, and evaluation criteria for assessing these technologies in industrial maintenance contexts. These questions guide a systematic examination of the current state, demonstrated outcomes, implementation barriers, and future directions for XR in maintenance applications.

The subsequent sections of this study are organized in the following manner. Section II outlines the systematic review methodology based on PRISMA guidelines. Section III presents results organized by technology prevalence, application areas, advantages, limitations, human-centric factors, and evaluation criteria. Section IV discusses the findings in the context of theoretical frameworks, contrasts the outcomes with prior studies, and describes the practical applications and study limitations. Section V presents concluding remarks, principal findings, and prospective research avenues.

II. Methodology

A. Research Questions

The aim of this systematic literature review (SLR) is to provide a comprehensive overview of the application of Extended Reality (XR) technologies in industrial maintenance, including the primary tasks, key advantages, limitations, and challenges. Additionally, this study seeks to identify the evaluation criteria used to assess XR technologies in industrial maintenance and explore how XR can promote human-centricity, a key concept in the Maintenance 5.0 framework. Furthermore, this SLR aims to provide researchers with insights into future work and research directions. To achieve these objectives, the following research questions (RQs) have been formulated:

- RQ1: What is the current state of XR technologies in industrial maintenance?
- RQ2: What are the benefits and potential of XR technologies in industrial maintenance?
- RQ3: What challenges and prospects exist for XR technologies in industrial maintenance?
- RQ4: How can XR technologies enhance human-centric industrial maintenance?
- RQ5: What are the evaluation criteria used in the literature to assess XR technologies in industrial maintenance?

B. Research String and Databases Selection

To answer the research questions, a comprehensive search string was formulated to capture relevant studies on the application of XR technologies in industrial maintenance. The search string used was: "industrial maintenance" AND ("virtual reality" OR "augmented reality" OR "mixed reality" OR "extended reality"). This search string covers the main concepts of the research topic, including industrial maintenance and the various types of XR technologies (virtual reality, augmented reality, mixed reality). The literature search was conducted using three major scientific databases: Scopus, ScienceDirect, and Web of Science. These databases were selected for their relevance and extensive coverage of peer-reviewed literature in the fields of engineering, technology, computer science and energy.

To guarantee that the review captured current and pertinent research on the topic, the scope was restricted to publications from January 1, 2014, and May 19, 2025. Additionally, only studies published in English were considered to maintain consistency and accessibility for the researchers. These date range and language filters were applied directly in the database search phase, before proceeding to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol.

The initial search yielded a total of 321 articles, distributed as follows:

- ScienceDirect: 168 articles.
- Scopus: 86 articles.
- Web of Science: 67 articles.

C. Selection of Primary Study

The initial search yielded 321 articles from the selected databases. These articles were then subjected to the PRISMA protocol (Fig. 1) to identify the most relevant studies for the systematic literature review.

First, duplicate articles were removed, resulting in 255 unique articles. These articles were then screened using their titles, abstracts, and keywords to assess their relevance to the research questions. Articles that were out of scope like "6G networks: Beyond Shannon towards semantic and goal-oriented communications" and "Deep Learning-Powered System for Real-Time Digital Meter Reading on Edge Devices," were excluded. However, articles addressing extended reality in industrial maintenance, including assembly and disassembly tasks, were retained, as these tasks are considered integral to industrial maintenance. This screening process resulted in the exclusion of 124 articles, leaving 131 articles for further review.

The remaining 131 articles are reviewed in full text and subjected to detailed analysis to assess their eligibility for inclusion in our study. During this stage, an additional 36 articles were excluded for the following reasons:

- Upon closer examination, 10 articles were found to be not directly relevant to the research questions.

- 14 articles were identified as literature review articles, which did not meet the inclusion criteria for primary studies.
- 12 articles were not accessible for full-text review.

Finally, a total of 95 articles were selected as primary studies to answer the research questions. These articles form the basis for the data extraction and synthesis stages of the systematic literature review.

D. Quality Assurance and Limitations of the Search Strategy

Several methodological considerations should be noted regarding the PRISMA implementation. First, the search was limited to three academic databases (Scopus, ScienceDirect, Web of Science), and grey literature sources such as technical reports, white papers, and industry documentation were not included. This may introduce publication bias, as studies reporting positive outcomes are more likely to be published in peer-reviewed venues. Second, the study screening and selection process was conducted by the first author and verified by the co-authors through discussion-based consensus rather than formal inter-rater reliability assessment. While this approach is common in systematic reviews within engineering disciplines, it represents a methodological limitation. Third, no formal risk-of-bias assessment tool (e.g., ROBINS-I or the Newcastle-Ottawa Scale) was applied to individual primary studies, as the heterogeneity of study designs—ranging from controlled experiments to case studies and framework proposals—made standardized quality scoring impractical. These limitations are acknowledged and should be considered when interpreting the synthesized findings.

E. Co-Authorship Analysis

Co-authorship analysis was performed using VOSviewer on the 95 primary study papers selected for the systematic literature review on extended reality (XR) in industrial maintenance. The analysis aimed to identify influential authors and collaborative networks within this specific subset of literature.

From the total pool of authors in the 95 papers, a minimum threshold of two documents per author was set. Out of the authors who met this threshold, the top 50 were selected for visualization. The resulting co-authorship network (see Fig. 2) reveals several distinct clusters of collaborating authors. The most prominent cluster includes Hakulinen, J., Burova, A., Ronkainen, K., Keskinen, T., and Mäkelä, J., forming a densely connected red network at the center of the visualization. Other notable clusters involve the blue grouping of Fiorentino, Michele and Gattullo, Michele in the upper right, and the green cluster with Bai, Xiaoliang, Liu, Wei, and He, Weiping in the upper center. Additional collaborations are visible with Al-harkan, I.M. and Alhag, M.H. (yellow nodes), as well as isolated researchers like Romero, I. and Yu, H. distributed around the periphery.

The size of each author's node represents their relative influence and contribution to the primary studies, based on the number of co-authored publications within this subset of literature. The links between authors signify collaborative relationships. The proximity of authors within the visualization suggests thematic or institutional similarities in their research within the scope of this review.

F. Keywords Co-occurrence Analysis

A co-occurrence analysis of keywords from the 95 primary studies was conducted using VOSviewer to identify the main themes in XR research for industrial maintenance. With a minimum threshold of three occurrences, 25 out of 564 keywords were selected for visualization.

The co-occurrence network (see Fig. 3) reveals clusters centered around "augmented reality," "industrial maintenance," and related concepts such as "maintenance operations," "human computer interaction," and "industry 4.0." The strong connection between "augmented reality" and "industrial maintenance" highlights the significance of AR in this domain. By using VOSviewer, the keyword "augmented reality" is the most frequent keyword (56 occurrences), followed by " maintenance" (34), " industrial maintenance" (33), and "virtual reality" (29). These results underscore the pivotal importance of AR and VR technologies in industrial maintenance research.

The analysis provides an overview of key themes and their interconnections, underlining the importance of human factors, performance optimization, and the integration of XR with Industry 4.0. This offers critical perspectives for understanding prevailing research patterns and identifying promising areas for investigation in XR for industrial maintenance.

III. Extended Reality in Industrial Maintenance: Research Results

A. Literature Analysis

1) Publications per year: Fig. 4 shows the number of selected primary papers on XR in industrial maintenance from 2014 to 2025. There is an overall upward trend, indicating growing research interest. The count of publications increased from 1 paper in 2014 to a peak of 13 papers in 2018. This was followed by a slight decline to 10 papers in both 2019 and 2020. The year 2021 saw a resurgence with 12 papers, followed by a decrease to 8 papers in 2022. Research output rebounded to 10 papers in 2023 and peaked again at 13 papers in 2024, matching the previous high from 2018. The data for 2025 shows only two papers, as the data collection period ended early in the year. The trend suggests sustained interest in XR research for industrial maintenance over the past decade, with consistently significant output from 2018 onwards despite some year-to-year fluctuations.

2) Publications per database: Fig. 5 illustrates the distribution of the selected primary papers across three databases: Scopus, ScienceDirect, and Web of Science. ScienceDirect contributes the largest portion of the papers at 51.6% (49 papers) of the total collection. Scopus accounts for a similar but slightly smaller proportion at 46.3% of the papers (44 papers). Web of Science appears to be minimally represented, accounting for only 2.1% of the total (2 papers). However, this underrepresentation can be attributed to the duplication removal process conducted using Zotero. A considerable number of papers from Web of Science were merged with their duplicates from Scopus and ScienceDirect. The decision to prioritize the Scopus and ScienceDirect versions of duplicated

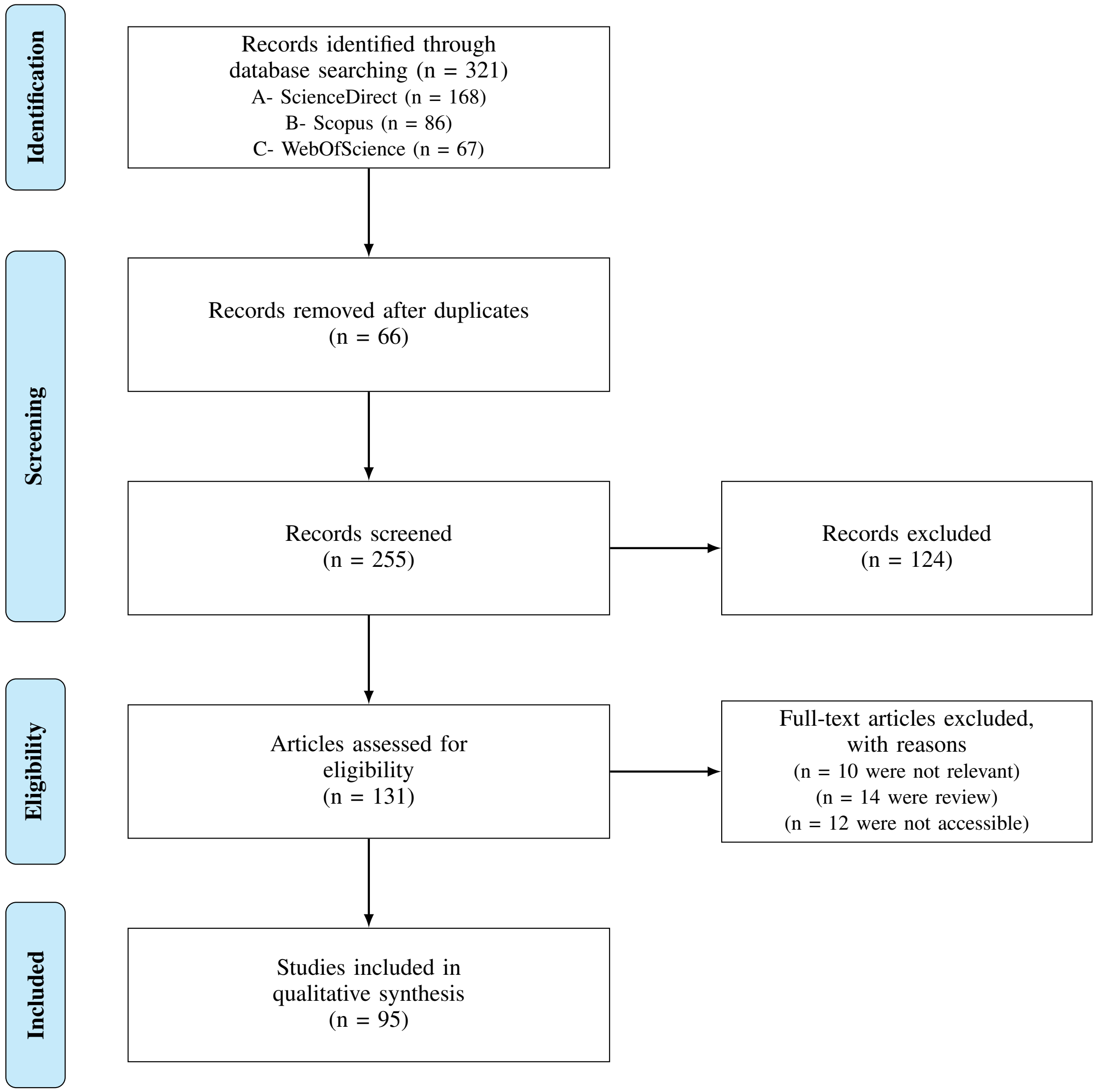

Fig. 1. The selection and filtering of primary studies (PRISMA flow diagram).

papers was based on the fact that these databases provide more extensive metadata, which facilitates and accelerates the analysis process. Consequently, the low percentage of papers from Web of Science does not necessarily reflect the database's actual contribution to the research on XR in industrial maintenance.

3) Publications per reference type: Fig. 6 illustrates the distribution of primary papers by reference type, categorized into journal articles, conference papers, and book chapters. Journal articles constitute the clear majority at 73.7% of the total, reflecting a strong preference for publishing XR research in peer-reviewed journals, which are generally seen as having a more rigorous review process and greater impact. Conference papers account for 25.3% of the publications, providing a platform for the rapid dissemination of knowledge and scholarly interaction. Book sections make up a minor portion at just 1.1% of the total. This distribution highlights the diverse avenues through which XR research in industrial maintenance is disseminated within the scientific community, while underscoring the predominance of journal publications in this field.

4) Publications per publication venues: Fig. 7 shows the distribution of papers across the top 10 publication venues. The most prominent sources include:

- Applied Sciences (Switzerland) journal (6 papers)
- Computers in Industry journal (6 papers)
- Advanced Engineering Informatics journal (4 papers)
- Lecture Notes in Computer Science Series (4 papers)
- Robotics and Computer-Integrated Manufacturing journal (4 papers)
- 16th IFAC Symposium on Information Control Problems in Manufacturing (3 papers)

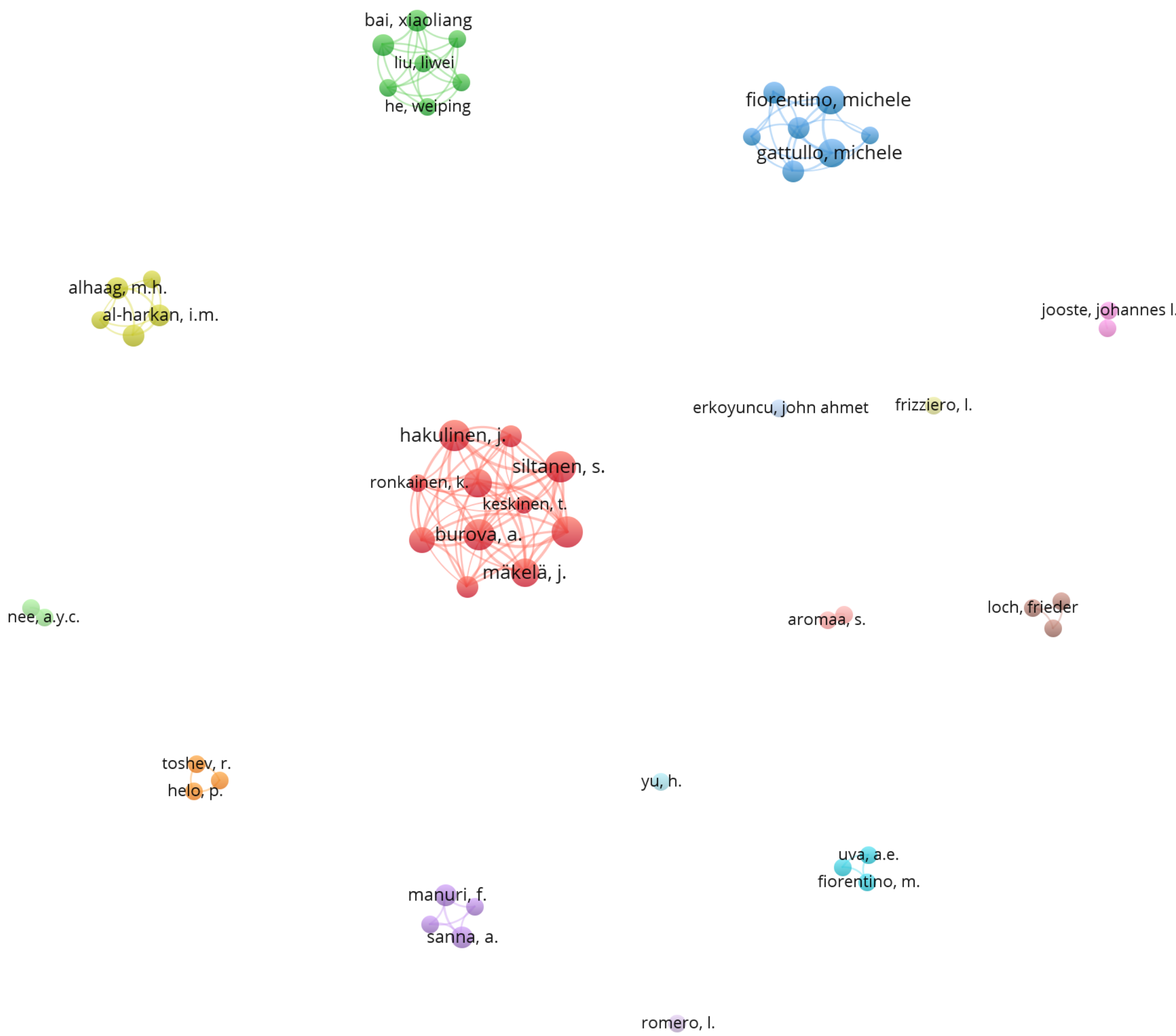

Fig. 2. Bibliometric map of co-authorship from VOSviewer using author names.

- 27th International Conference on Production Research (3 papers)
- 56th CIRP International Conference on Manufacturing Systems (2 papers)
- ACM International Conference Proceeding Series (2 papers)
- Applied Ergonomics journal (2 papers)

The distribution reveals that both specialized industrial and manufacturing journals, as well as computer science publications, serve as essential platforms for XR in industrial maintenance research. The relatively even distribution across these top venues indicates a multidisciplinary research landscape, with papers appearing in publications covering diverse areas, including applied sciences, computer science, engineering informatics, robotics, manufacturing, and ergonomics.

B. Extended Reality in Industrial Maintenance

1) Current state of extended reality in industrial maintenance: The analysis of 95 studies reveals a diverse and rapidly evolving landscape of extended reality (XR) technologies in industrial maintenance. This subsection outlines the key findings regarding the current state of these technologies.

a) Prevalence and distribution of XR technologies: The analysis of XR technology adoption across the 95 primary studies reveals clear patterns in the prevalence and distribution of different reality technologies in industrial maintenance applications. Fig. 8 presents the overall distribution of XR technologies identified in the literature.

Augmented Reality (AR) emerges as the dominant technology, appearing in 68 studies (71.6% of the total), making it the most widely adopted XR technology for industrial maintenance applications. Studies [2], [3] showcase AR's effectiveness in providing visual instructions for maintenance tasks, while studies [4], [5] highlight its use in enhancing worker performance and reducing errors. Virtual Reality (VR) is the second-most

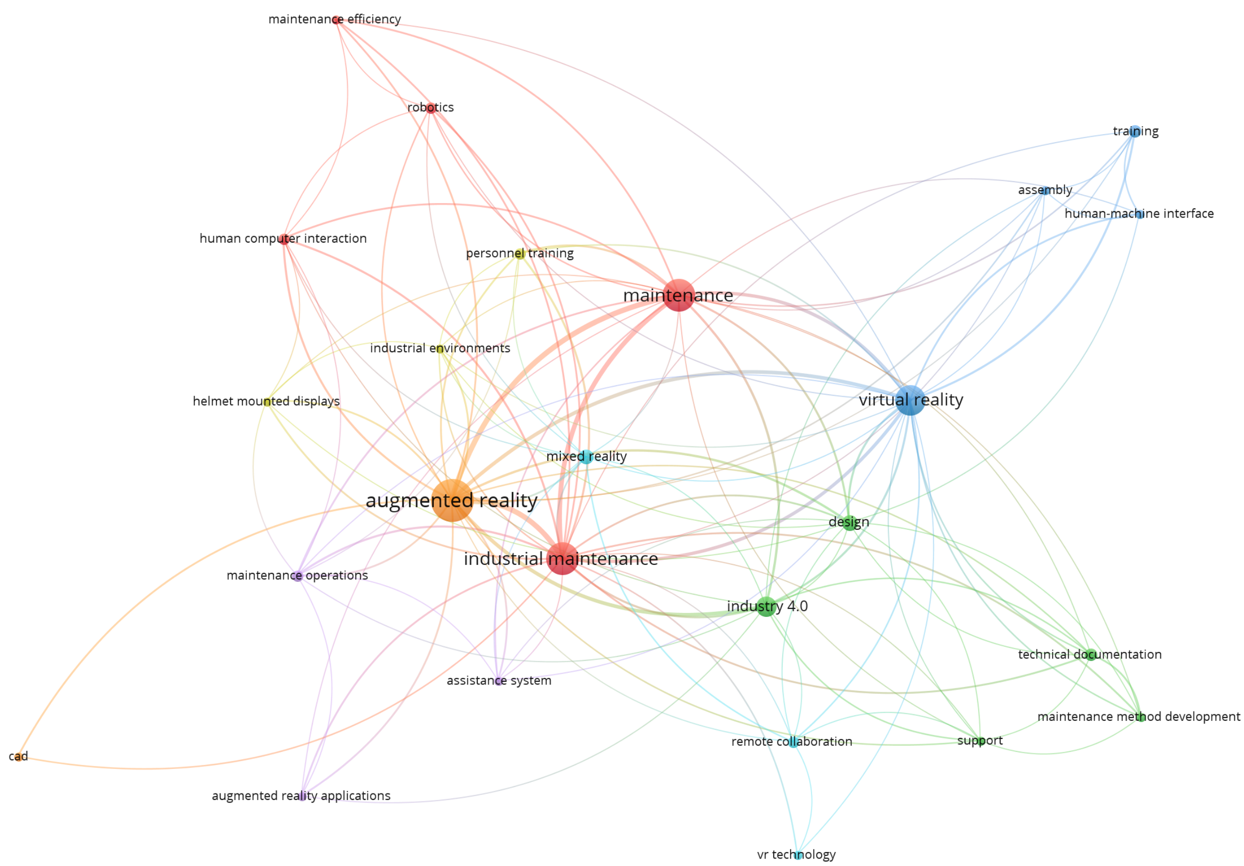

Fig. 3. Bibliometric map of author keywords from VOSviewer.

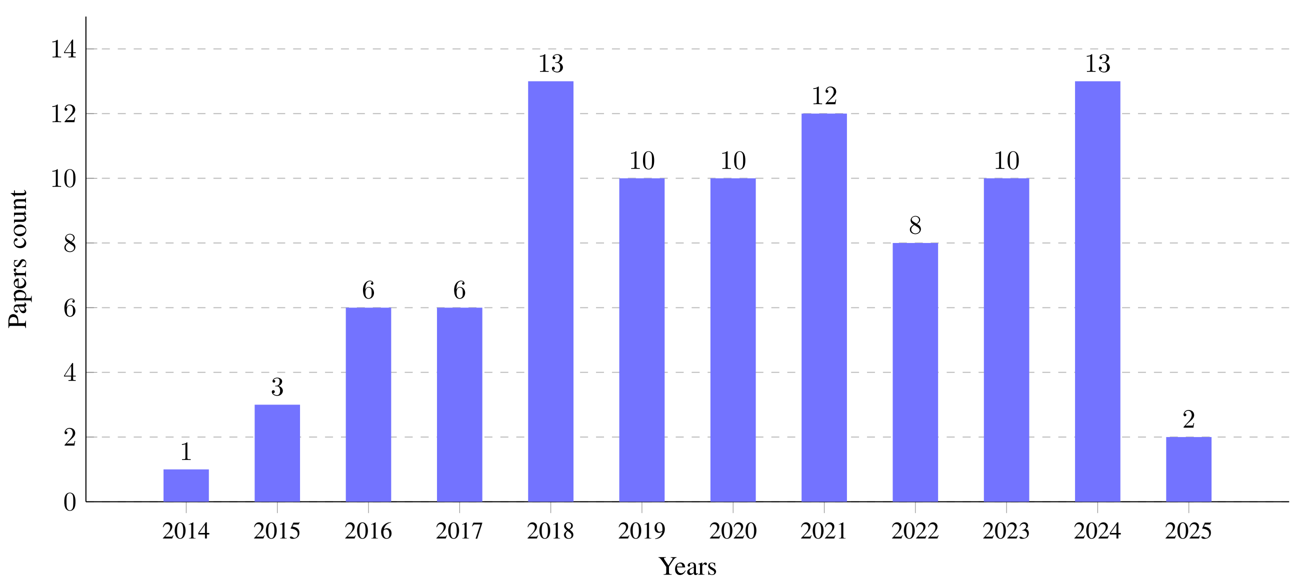

Fig. 4. Number of primary papers per year.

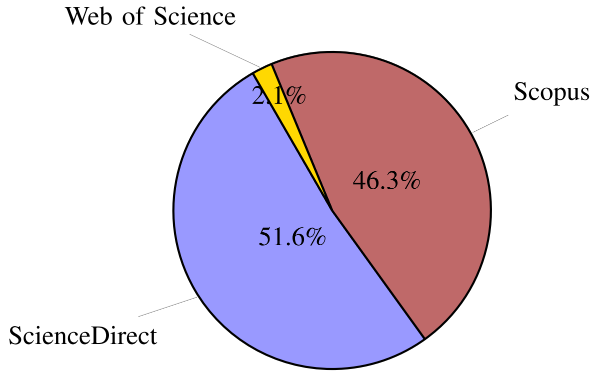

Fig. 5. Number of primary papers per database.

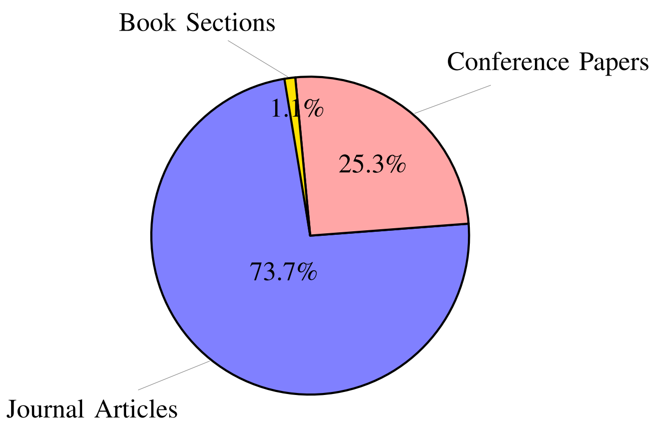

Fig. 6. Number of primary papers per reference type.

prevalent technology, used in 37 studies (38.9%). Studies [10], [12], [13] illustrate VR's capacity to create immersive, risk-free environments for maintenance personnel to practice complex procedures. Mixed Reality (MR) appears in only 6 studies (6.3%). Studies [68], [70], [71] demonstrate MR's potential to bridge the gap between on-site technicians and remote experts, facilitating real-time guidance and problem-solving.

A small number of papers (3, representing 3.1%) explicitly use the term "Extended Reality" (XR) in their work, typically in studies that present conceptual frameworks or methodologies applicable across multiple reality technologies. 1 paper in our dataset mentioned augmented virtuality as technology.

It is worth noting that 14 studies (14.7%) employed multiple XR technologies within the same research, with the most common combination being AR+VR (7 studies). Notably, three studies [10], [34], [70] incorporated all three main technologies (AR+VR+MR) in their work, with study [34] integrate them along with explicit XR framework development. This trend toward multi-technology approaches highlights the complementary nature of different XR modalities and suggests a growing interest in comprehensive XR ecosystems for maintenance applications.

C. Temporal Trends in XR Technology Adoption

The chronological analysis of XR technology adoption reveals significant trends in the field's evolution (Fig. 9). The three evolutionary phases were delineated based on a combination of qualitative thematic shifts and observable inflection points in the data. The boundary between Phase 1 and Phase 2 (2017–2018) corresponds to the sharp increase in publication volume (from 6 to 13 papers) and the emergence of cognitive enhancement as a research focus, coinciding with the commercial availability of Microsoft HoloLens and its rapid adoption in industrial AR studies. The boundary between Phase 2 and Phase 3 (2021–2022) aligns with the appearance of AI-integrated systems and automatic content generation approaches in the literature, reflecting the broader convergence of XR with machine learning and IoT technologies. These boundaries are therefore informed by convergent technological, thematic, and bibliometric indicators rather than purely statistical criteria. Early research (2014-2017) showed a strong preference for AR, which dominated the initial studies in industrial maintenance. Study [22] represents the first comprehensive AR implementation for maintenance tasks in our dataset, focusing on providing visual guidance on a screen-based video see-through AR system for motorcycle engine maintenance.

From 2017 onward, there was a noticeable increase in VR adoption, with powerful representation in 2018, 2021, and 2024. The years 2021-2022 mark a potential inflection point, where VR studies temporarily equaled or exceeded AR studies in quantity. Study [10] exemplifies this trend, presenting a VR-based methodology for assessing cognitive conditions during assembly training.

Mixed Reality, representing the most recent technological evolution in the reality continuum, first appeared in our dataset in 2020 [8] and has shown consistent but limited adoption through 2024. This slower uptake may reflect the nascent state of MR technology and its development ecosystem compared to more established AR and VR platforms.

The most recent years (2023-2025) have seen a renewed interest in AR applications, a diversification of technology approaches with more MR studies, and an increasing mention of XR as an overarching concept. This evolution suggests the field is moving toward a more integrated view of reality technologies while maintaining a strong interest in application-specific implementations.

D. Technology Distribution by Research Focus

The prevalence of specific XR technologies correlates strongly with the primary research focus and application context. AR dominates in studies focused on real-time guidance [15], [21], [27], [41], [43], maintenance instructions [22], [25], [26], [36], and on-site assistance [5], [7], [9]. This aligns with AR's fundamental capability to overlay digital information on real-world equipment, making it particularly suited for in-situ maintenance support.

VR is predominantly employed in studies focused on training and simulation of maintenance procedures [10], [30], [35], [48], [50], [63], [67], [64] and collaborative design reviews [11], [13], [32]. The immersive nature of VR creates controlled, risk-free environments that are ideal for skill development and scenario-based learning before interacting with physical equipment.

Mixed Reality applications appear most frequently in studies focusing on remote collaboration and tasks requiring so-

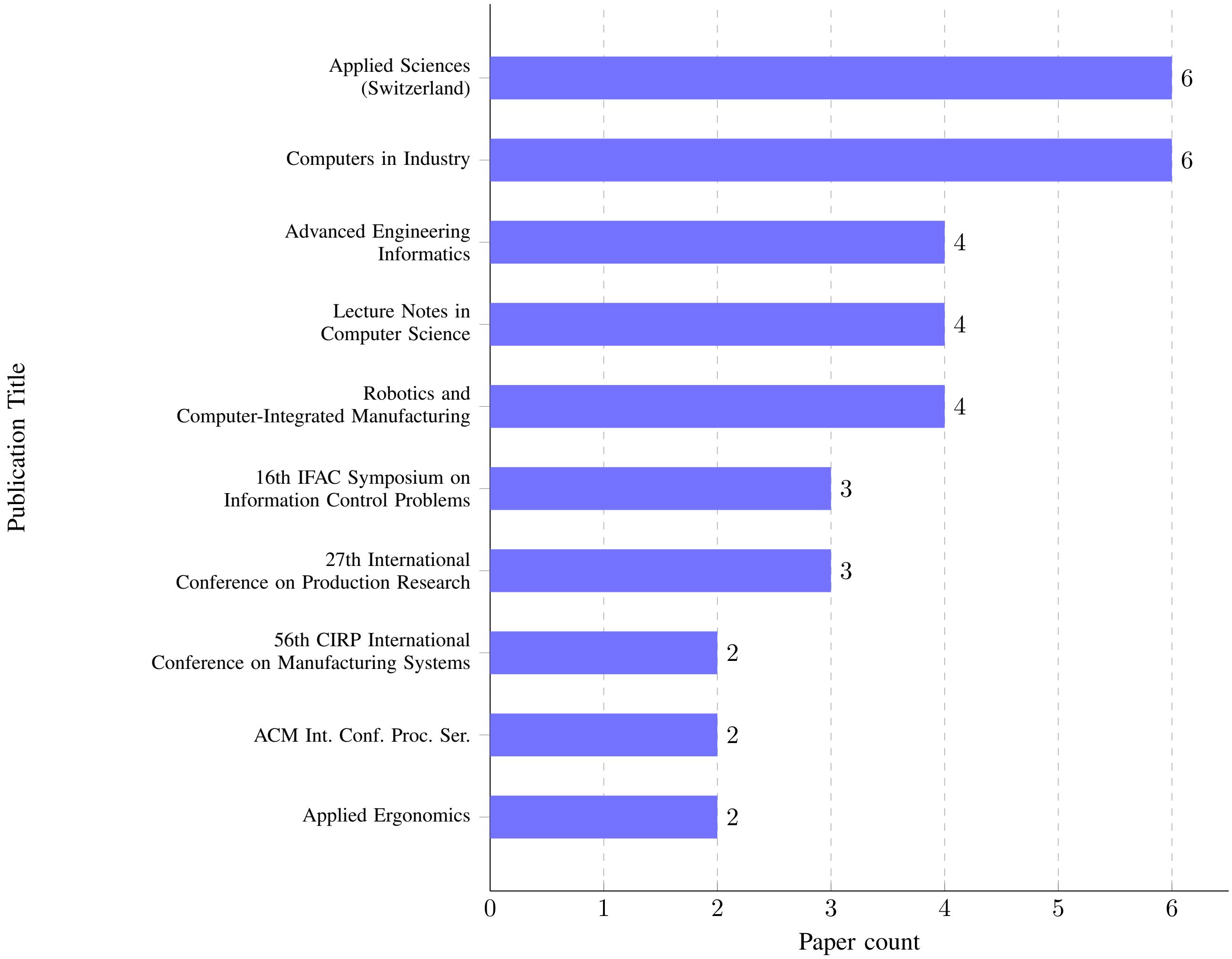

Fig. 7. Number of primary papers per publication venues.

phisticated spatial understanding [8], [14], [68], [70], [71]. The combination of real-world anchoring with immersive virtual elements makes MR particularly effective for collaborative troubleshooting and complex spatial tasks.

The chronological and application-based distribution patterns reflect both technological evolution and the maturing understanding of which XR technology best suits specific maintenance contexts. This suggests that industrial maintenance is shifting toward a task-specific application of XR technologies, rather than a one-size-fits-all approach.

1) Hardware trends: The analysis of hardware platforms across the reviewed studies reveals clear preferences and evolutionary trends in the adoption of XR devices for industrial maintenance applications. Table I presents the distribution of hardware platforms identified in the primary studies.

E. Head-Mounted Displays (HMDs)

Head-mounted displays represent the most frequently utilized hardware category in industrial maintenance applications, with Microsoft HoloLens being the dominant platform, mentioned in 18 studies. First appearing in our dataset in 2017 [21], HoloLens quickly established itself as the preferred option for industrial AR implementations, particularly for hands-free maintenance guidance [33], [60], [62], [66]. The prevalence of HoloLens can be attributed to its enterprise focus, robust tracking capabilities, and integrated computing power, making it suitable for industrial environments.

For VR applications, the HTC Vive headset emerged as the primary choice in four studies [12], [48], [64], [77], with limited mentions of other platforms, such as the Valve Index [8] and Oculus/Meta devices [79]. Study [8] represents an interesting case where a Valve Index headset was utilized for remote teleoperation of a mobile manipulator robot in cleanroom environments, highlighting the adoption of high-end consumer VR hardware for specialized industrial applications.

The temporal analysis of HMD adoption shows a distinct evolution in hardware preferences. Early studies (2014-2016) primarily employed non-HMD approaches, such as projector-based systems [22]. From 2017 onward, we have observed a clear shift toward head-mounted solutions, characterized by increasing sophistication in tracking and display capabilities. Studies [2], [3], [4], [75] illustrate the recent trend toward using HMDs to reduce task completion time, mental workload, and

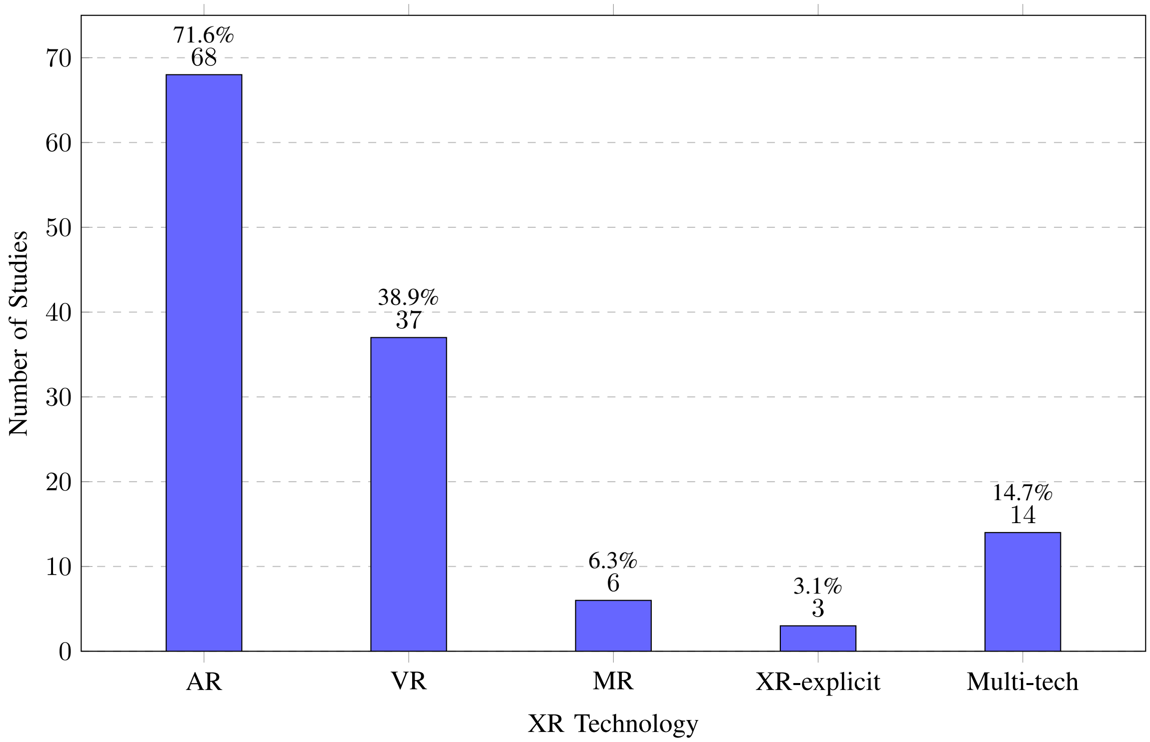

Fig. 8. Distribution of XR technologies across 95 primary studies. Percentages sum to over 100% as 14.7% of studies employed multiple technologies simultaneously.

improve cognitive processing for complex tasks.

F. Handheld Devices

Tablets (9 studies) and smartphones (6 studies) constitute the second most common hardware category, particularly prevalent in AR implementations where hands-free operation is not critical. Study [31] compared the effectiveness of AR on smart glasses (Vuzix M100) with AR on tablets, finding that smart glasses performed better in metrics such as completion time (-13% vs. -3% compared to paper) and scored higher in usability ratings and operator reliance. At the same time, both AR solutions demonstrated similar benefits in reducing errors compared to paper-based instructions. Studies [45], [69] illustrate the use of these devices, highlighting their advantages in terms of accessibility and user familiarity.

The temporal distribution shows consistent use of handheld devices throughout the review period, with notable spikes in 2016, 2018, and 2024. This persistent adoption of handheld solutions, even as HMDs became more sophisticated, suggests that different form factors serve complementary roles in industrial maintenance. Study [33] explicitly explored this complementarity by proposing a multi-device assistive system that leverages the strengths of both HMDs and handheld devices across different maintenance phases.

G. Other Hardware Platforms

Several supplementary hardware technologies appear in the reviewed studies, with haptic devices (6 studies) being the most prominent. Early implementations [1] utilized dedicated haptic systems like the Phantom Desktop, while more recent studies [39], [48] integrate haptic feedback with VR environments to enhance training realism.

Projector-based AR systems (4 studies) represent an alternative approach that avoids the need for personal displays entirely. Study [37] presents a portable camera-projector system for telemaintenance that enables spatially-registered annotations projected directly onto the work environment. This approach offers advantages in collaborative settings where multiple technicians need to view the same augmented workspace simultaneously.

Motion tracking technologies like Leap Motion controllers (2 studies) appear in applications requiring precise hand interaction, particularly for VR-based training systems [48], [49], [50]. These technologies enable natural gesture-based interaction with virtual environments, enhancing the realism of maintenance simulations.

H. Hardware Evolution and Limitations

The evolution of hardware platforms over the review period (2014-2025) reflects broader technological trends in the development of XR. Early studies employed more experimental or custom hardware configurations, whereas recent research has increasingly leveraged commercial off-the-shelf solutions with standardized development environments.

Several studies [5], [7], [15], [55], [59], [60], [62], [72] explicitly discuss hardware limitations as significant challenges, particularly regarding the limited field of view, ergonomic issues with prolonged use, and environmental constraints in industrial settings. Study [31] notes specific issues with smart

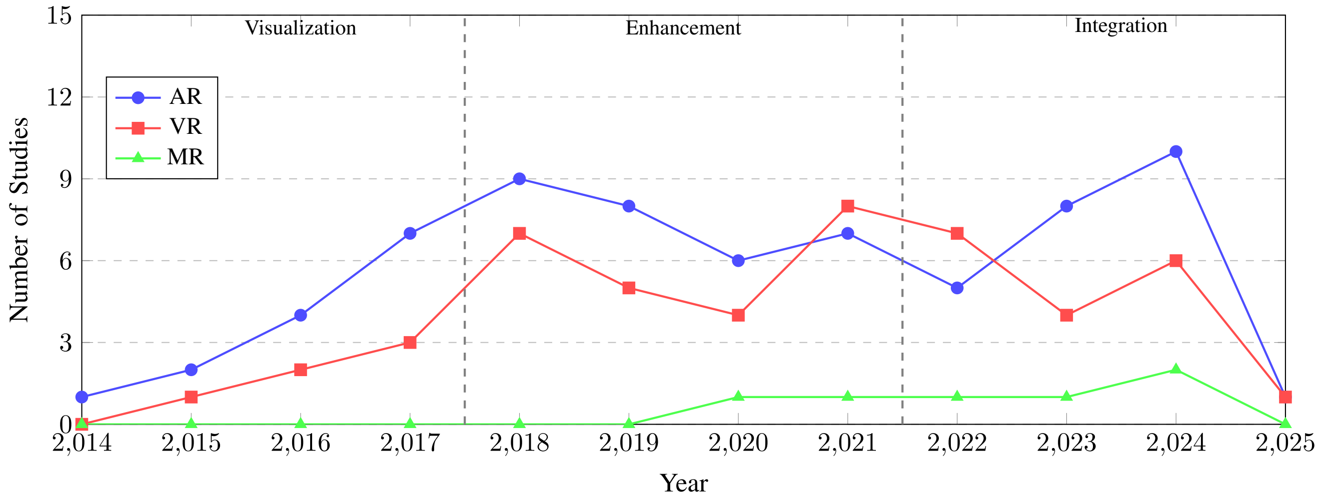

Fig. 9. Temporal evolution of XR technologies in industrial maintenance (2014-2025), showing three distinct evolutionary phases.

glasses, including comfort problems and a restricted screen size, which makes augmentations difficult to distinguish. This can cause users to close one eye to see correctly and requires constant visual focus switching, leading to visual strain.

The hardware trends suggest an industry in transition, with increasing standardization around enterprise-focused platforms, such as HoloLens for AR applications and HTC Vive for VR applications, while maintaining a pragmatic approach to device selection based on specific maintenance contexts and requirements.

1) Software and development: The software platforms, development frameworks, and implementation approaches used across the reviewed studies reveal essential patterns in how XR technologies are being integrated into industrial maintenance applications. This subsection examines the prominent software trends identified in the literature (Table II).

I. Development Platforms and Game Engines

Unity (identified in 18 studies) emerges as the dominant development platform across all XR technology types, serving as the foundation for applications in AR, VR, and MR. Its prevalence can be attributed to its cross-platform capabilities, extensive asset ecosystem, and relatively accessible learning curve. Study [1] used Unity to develop a haptic virtual reality platform for assembly tasks, while study [46] employed it to create an AR application for providing adaptive instructions for machine operation tasks. Study [12] also exemplifies the typical Unity-based development approach, utilizing the platform to create a VR system with AR simulation and gaze tracking for prototyping industrial maintenance solutions.

Unreal Engine appears in significantly fewer studies (only 1 explicit mention), despite its reputation for high-fidelity graphics and robust performance. Study [64] uses Unreal Engine 4 to develop a VR application for power plant maintenance training, suggesting that this engine may be preferred for applications requiring advanced visual fidelity.

The preference for Unity across the majority of studies indicates a maturation of the development ecosystem, where researchers and developers increasingly leverage established platforms rather than developing custom solutions from scratch. This standardization facilitates more rapid prototyping and reduces technical barriers to XR implementation in industrial contexts.

J. AR/VR Software Development Kits (SDKs)

Vuforia emerges as the most widely utilized AR SDK (6 studies). Studies [15], [21], [79] utilized Vuforia in combination with Unity to implement visual tracking and registration for maintenance tasks. The prevalence of Vuforia aligns with its established position in the AR development ecosystem, extensive documentation, and relatively stable performance across different deployment scenarios.

Other SDKs appear less frequently but highlight the diversification of development approaches. OpenXR and SteamVR in [81] represent newer standards-based approaches to VR development, while Microsoft's Mixed Reality Toolkit (MRTK) appears in [75] focused on HoloLens applications. Study [81] specifically mentions a combination of OpenXR, XRInteractionToolkit, and SteamVR packages within Unity, illustrating the trend toward utilizing multiple complementary frameworks within a single development environment.

K. Programming Languages and Technical Approaches

Specific programming languages receive relatively few explicit mentions in the methodology sections of the reviewed studies. Python (3 studies) is the most frequently cited, particularly in studies involving machine learning components or data processing pipelines [69], [74], [75]. C++ and C# are also used as programming languages with lower frequency, 1 explicit mention each [1], [34], with C# specifically appearing in a study focused on XR-based serious game development for Compressed Air System (CAS) maintenance training, where it was paired with the Unity development platform to create an immersive learning experience that incorporated 3D models and the XR Interaction Toolkit [34]. Study [1] presents a more complex development approach, combining OpenHaptics, PhysX, and OpenGL/GLUT libraries to create a haptic

TABLE I. Overview of Hardware Platforms used in XR-Based Industrial Maintenance Applications (2014–2025).

Category	Dominant Platforms (Count)	Primary Application Patterns
Head-Mounted Displays (HMDs)	• Microsoft HoloLens (18) • HTC Vive (4) • Valve Index (1) • Oculus/Meta devices (1)	• **HoloLens:** Dominant standard for hands-free AR maintenance guidance. • **HTC/Oculus:** Primarily used for immersive VR training simulations. • **Valve:** Specific usage for remote teleoperation in cleanrooms.
Handheld Devices	• Tablets (9) • Smartphones (6)	• **Tablets/Smartphones:** AR implementations where hands-free operation is not critical like inspection tasks requiring larger visual interfaces.
Supplementary Technologies	• Haptic devices (6) • Projector-based AR (4) • Motion tracking (2)	• **Haptics:** Integrated to enhance physical realism in VR training. • **Projectors:** Used for collaborative telemaintenance without wearable gear. • **Tracking:** Leap Motion used for natural gesture-based interactions.

VR platform for assembly planning and assessment. Such multi-library implementations are less common in more recent studies, suggesting a shift toward more integrated development environments that encapsulate these functionalities.

L. *Content Authoring Approaches*

A notable trend across the reviewed studies is the increasing focus on content authoring approaches that simplify the creation of XR maintenance applications without requiring extensive programming expertise. Studies [21], [23], [56], [58], [69], [72] present frameworks or methodologies specifically designed to enable non-technical domain experts to create and manage XR content for maintenance tasks.

Study [69] exemplifies this trend with an automatic content creation system for AR maintenance applications that extracts information from electronic manuals to generate AR-ready content accessible via QR codes. Similarly, the study [56] presents the INTERVALES framework that simplifies AR/VR content authoring for industrial applications by providing a modular architecture that supports both IT developers and domain experts.

This evolution toward simplified content creation constitutes a significant advancement in the practical deployment of XR in industrial maintenance, addressing a primary obstacle to implementation identified in earlier research — the high technical expertise traditionally required to develop and maintain XR applications.

M. *Integration with Industrial Systems*

The incorporation of XR applications into established industrial systems and information infrastructure represents an emerging focus area in more recent studies. Several papers [33], [38], [41], [45], [53] discuss approaches for connecting XR applications with industrial IoT systems, databases, and enterprise asset management systems.

Study [38] presents an integrated approach combining IoT, machine learning, and AR within a comprehensive predictive maintenance framework. Similarly, study [79] demonstrates a unified platform integrating IoT, analytical processing, AR, and VR technologies to support equipment surveillance and maintenance. These integrated approaches represent a maturation of the field, moving beyond isolated XR implementations toward more holistic solutions that leverage multiple complementary technologies.

The software and development trends reflect an industry transitioning from experimental proof-of-concept implementations toward more standardized and integrated approaches, with increasing emphasis on reducing technical barriers to adoption and enhancing integration with existing industrial ecosystems.

1) Application areas: The analysis of primary studies reveals distinct patterns in the application of XR technologies across maintenance tasks and scenarios in industrial environments. This subsection categorizes and examines the primary application areas identified in the literature, as summarized in Fig. 10.

N. *Procedural Guidance and Task Assistance*

Providing step-by-step guidance for maintenance procedures was the most prevalent application area (41 studies, 43.1%), with Augmented Reality the predominant technology in this domain. AR's ability to overlay digital information directly onto physical equipment makes it particularly suited for procedural guidance.

Studies [4], [15], [22], [27], [43], [75] showcase AR's application for guiding users through maintenance procedures with visual overlays. Study [22] demonstrates an early implementation using a screen-based video see-through AR system for motorcycle engine maintenance, reporting a 38% improvement in completion time and 92.4% reduction in error rate compared to traditional paper manuals. Recently, study [75] developed the TAGGAR system, which focuses on providing AR task guidance for procedural maintenance tasks by rendering virtual hand animations that demonstrate required

TABLE II. SUMMARY OF SOFTWARE TRENDS AND DEVELOPMENT FRAMEWORKS

Category	Dominant Tech	Key Implementation Patterns	Refs.
Game Engines	Unity, Unreal Engine	• Unity is dominant (18 studies) due to cross-platform assets. • Unreal used specifically for high-fidelity needs. • Shift from custom engines to standardized platforms.	[8], [12], [15], [21], [27], [29], [34], [46], [48], [50], [57], [65], [74], [75], [77], [79], [80], [81], [64]
SDKs	Vuforia, OpenXR, MRTK	• Vuforia remains the standard for visual tracking. • Adoption of OpenXR/MRTK reflects a move toward open standards and specific HoloLens optimization.	[15], [21], [29], [57], [73], [75], [79]
Languages	Python, C#, C++	• Python: Used for ML and data pipelines. • C#: Primary language for Unity-based interaction. • C++: Usage declining; mostly for legacy or haptic libraries.	[1], [34], [69], [74], [75]
Authoring	Low-code Frameworks	• Focus on simplifying creation for non-technical experts. • Automated content generation from manual data (e.g., QR codes).	[21], [56], [69]
Integration	IoT, EAM, Cloud	• Move from isolated apps to holistic ecosystems. • Integration with live IoT data and predictive maintenance systems.	[38], [45], [79], [81]

actions. This enables AR-based guidance for tasks such as pressing buttons, twisting knobs, pulling objects, and picking up/placing items.

The presentation modalities for procedural guidance have evolved considerably over the review period. Early studies primarily used text and simple 2D graphics, whereas more recent research has explored 3D animations [4], standardized graphical symbols [25], [26], [61], and context-aware adaptive interfaces [15], [21], [55]. Study [36] explicitly compares three different AR presentation modes for maintenance instructions in blind areas, finding that in-situ 3D presentations with X-ray rendering outperform 3D side-by-side in terms of completion time.

Several studies [21], [46], [47], [65], [76], [78] focus on adapting the level of guidance to match user expertise and task complexity. Study [47] proposes a system that combines collaborative robotics and AR, designed to accommodate workers with different experience levels through robotic assistance and AR guidance in car panel fitting operations. Study [76] introduces an approach to developing Augmented Reality-based Adaptive Assistance Systems (ARAAS) that adapt content to operator characteristics.

O. Training and Skill Development

Training is the second most common application area (mentioned in 32 studies, 33.6%), serving as a cornerstone use case for XR technologies in industrial maintenance. The engaging and interactive characteristics of XR environments offer a safe, controlled space for skill development without the risks or resource constraints of real-world training scenarios.

Virtual Reality dominates the training domain, with studies [10], [30], [35], [63], [64], [77] showcasing comprehensive VR-based training systems for various maintenance procedures. Study [35] demonstrates how VR training enhances performance in intricate industrial assembly tasks compared to traditional methods, showing improved performance and training permanency. Similarly, study [77] compares VR-based training with traditional paper-based approaches for wiring electric motors, reporting a 10% improvement in task completion time.

Augmented Reality training applications focus more on in-situ guidance and real-time skill development. Study [29] presents an AR mobile application for training on CNC lathe maintenance and repair, highlighting improved student motivation and learning outcomes. The hybrid approach of using AR during actual maintenance tasks blurs the line between training and operational support, as illustrated in study [17], which compares AR, VR, and video-based training for manual assembly tasks.

More recent studies [80], [81] demonstrate an evolution toward more sophisticated training approaches, incorporating game-based elements, adaptive difficulty, and integration with real equipment data. Study [80] introduces an XR-based serious game for compressed air system maintenance, while study [81] presents a modular framework for developing VR environments to enhance safety training during human-robot collaboration scenarios.

P. Assembly and Disassembly Support

Assembly and disassembly tasks appear as specific focus areas within the broader maintenance domain, with assembly operations mentioned in 24 studies (25.2%) and disassembly processes in 5 studies (5.2%). These complementary processes represent fundamental maintenance activities that benefit significantly from XR guidance.

AR dominates dis/assembly support applications, as demonstrated in studies [4], [16], [24], [41], [57], [59]. Study [41] introduces an AR solution that facilitates the assembly of multi-stage rotors used in turbine-based combined-cycle engines. Study [16] presents an AR-assisted framework for product disassembly (ARDIS) to improve efficiency in product maintenance and remanufacturing processes. Similarly, study [24] applies Design for Disassembly (DfD) principles with AR visualization to optimize the disassembly process for industrial components.

VR applications in this domain focus more on planning, verification and simulation aspects of assembly/disassembly. Study [1] presents a haptic VR platform for planning, performing and assessing virtual assemblies, providing force feedback and realistic part behavior. Study [67] introduces a multimodal system for verifying assembly procedures and product design in VR using CAD models and haptic feedback.

Mixed Reality applications for assembly tasks appear in studies [68], [70], with a particular focus on remote collaboration scenarios. Study [70] presents an adaptive MR remote collaboration system that provides clear, detailed, and spatially correct instructions for assembly tasks, demonstrating improved performance and reduced workload compared to a typical remote collaboration interface called RECI.

Q. Remote Assistance and Collaboration

Remote expert support and collaborative maintenance emerged as a significant application area (22 studies, 23.1%), reflecting the growing importance of distributed work and knowledge sharing in industrial settings. All three major XR technology types (AR, VR, and MR) are well-represented in this domain, each offering distinct advantages.

AR-based remote assistance systems are demonstrated in studies [7], [9], [37], [66], with study [37] presenting a projector-based AR system for telemaintenance that enables bidirectional spatial communication between remote experts and on-site technicians. AR's ability to provide spatially-anchored guidance in the real environment makes it particularly effective for remote support scenarios. VR-based collaborative environments have been explored in studies [11], [13], [14], [32], focusing on shared virtual spaces for maintenance planning and knowledge exchange. Study [32] examines the application of collaborative VR for reviewing maintenance documentation and assessing risk, highlighting numerous benefits for globally distributed teams.

The most sophisticated remote collaboration approaches utilize Mixed Reality, as shown in studies [68], [70], [71]. Study [70] presents an MR remote collaboration system (AGICA) that supports adaptive instruction generation based on context awareness, while study [71] introduces a novel MR system that enables remote experts to create 3D models for annotating spatial areas with visual notifications about interactions.

R. Inspection and Diagnostic Support

Inspection tasks (5 studies, 5.2%) and diagnostic/troubleshooting support (3 studies, 3.1%) represent more specialized application areas where XR technologies augment human perceptual and analytical capabilities. These applications often combine XR with additional sensing modalities or analytical tools.

Study [20] presents an innovative system (AROD) that combines AR with an electronic nose (e-nose) for odor detection during maintenance, displaying relevant information to detected odors via a HoloLens headset. Similarly, study [51] introduces MANTRA, a novel AR system that combines AR and infrared thermography for industrial maintenance, automatically aligning virtual information and temperature data with 3D objects.

In the inspection domain, study [41] presents an AR-based system for guiding the assembly of multi-stage rotors, incorporating measurement equipment to provide real-time visual assembly guidance tailored to precision requirements. Study [76] applies an adaptive AR assistance system specifically to landing gear inspection operations, highlighting areas to measure and displaying corresponding tolerance values, resulting in reduced execution time and improved information access.

Recent studies indicate an increasing integration of XR with other Industry 4.0 technologies to enhance diagnostic capabilities. Study [53] presents a methodology for automatic segmentation and analysis of anomalies in solar PV modules using unsupervised sensing algorithms coupled with 3D AR visualization. Study [79] demonstrates an integrated system combining IoT, data analysis, AR and VR for equipment monitoring and maintenance, enhancing predictive maintenance capabilities and operational efficiency.

The literature identifies diverse and evolving XR use cases in industrial maintenance. While specific applications, such as training and procedural guidance, are well-established across the review period, newer applications, including integrated diagnostic systems and adaptive assistance frameworks, represent emerging trends that leverage XR's capabilities in increasingly sophisticated ways.

S. Advantages of Extended Reality in Industrial Maintenance

The analysis of primary studies reveals five major categories of advantages associated with XR technologies in industrial maintenance contexts, as summarized in Table III. These benefits collectively demonstrate the transformative potential of these technologies across various aspects of maintenance operations.

1) Efficiency and performance improvement: Improved operational efficiency represents one of the most frequently cited advantages of XR technologies. AR applications consistently demonstrate significant time savings in maintenance execution. Study [22] reports a 38% improvement in completion time for motorcycle engine maintenance tasks compared to traditional paper manuals. Study [76] presents a methodology for designing Augmented Reality-based Adaptive Assistance Systems (ARAAS). The system supports inspection operations of landing gear components during maintenance, repair, and overhaul (MRO) activities, resulting in a 10% reduction in total inspection time.

The efficiency gains are pronounced for complex maintenance tasks as well. Study [2] demonstrates that AR instructions significantly reduce task completion time, particularly for complex maintenance activities, whereas they have a smaller impact on simpler tasks. Similarly, study [3] shows that task completion time is reduced with AR-based instruction methods compared to paper-based methods, especially for complex tasks involving a piston pump system. This finding suggests that escalating benefits occur as task complexity increases — a valuable characteristic in industrial environments, where complex procedures pose the most significant challenges.

The cost implications of these efficiency improvements stem from decreased downtime [7], [11], reduced travel requirements for experts [7], [9], [11], and more efficient use of

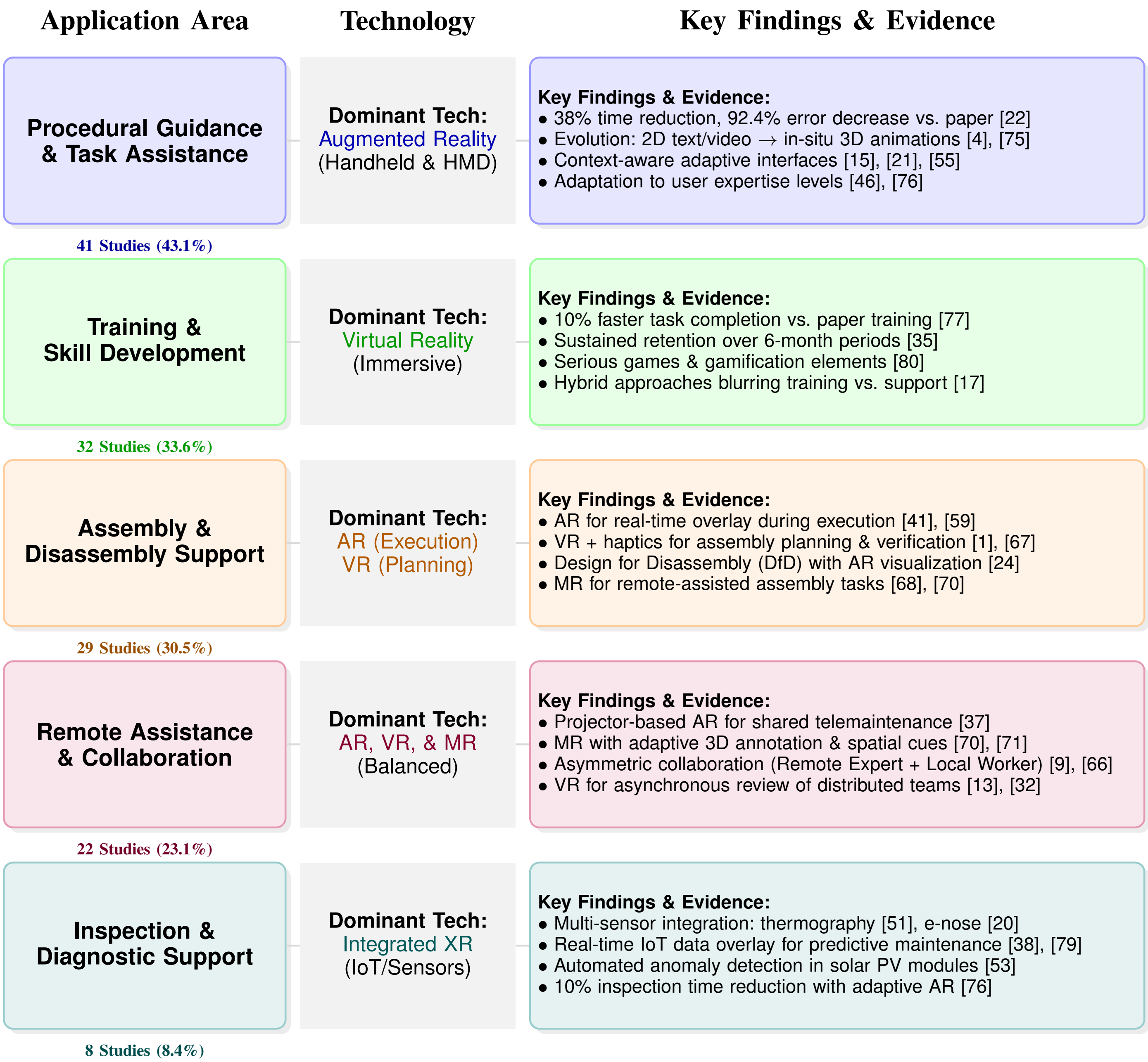

Fig. 10. Taxonomy of primary application areas in XR industrial maintenance, mapping study frequency, dominant technologies, and key empirical findings with supporting references.

personnel [2], [9], [11]. Notably, study [45] identifies cost reduction as a direct benefit of AR-based maintenance assistance. In contrast, study [64] highlights the economic advantages of VR training over physical equipment use, including reduced costs, faster training delivery, and the elimination of expensive physical resources.

2) Quality enhancement and error reduction: Error reduction emerges as a significant advantage in reviewed studies. The visual guidance and procedural structure provided by XR applications contribute to fewer errors and more consistent performance. Study [22] demonstrates a remarkable 92.4% reduction in error rates when using AR for maintenance tasks compared to paper-based instructions. Similarly, study [31] found that AR guidance resulted in fewer errors compared to paper instructions during maintenance tasks.

VR applications show comparable benefits in training contexts. Study [35] reports that VR-based training for industrial assembly tasks led to improved performance and fewer errors during subsequent real-world execution. The immersive environment enables repeated practice without risk, improving proficiency before physical interaction with equipment.

MR offers unique advantages for quality in collaborative scenarios. Study [70] presents an MR system that reduced errors by providing spatially correct instructions for assembly

TABLE III. SUMMARY OF KEY ADVANTAGES AND BENEFITS OF XR IN INDUSTRIAL MAINTENANCE

Category	Key Benefits & Empirical Evidence	Refs.
Efficiency & Performance	• **Time Reduction:** Significant savings in execution time (e.g., 38% improvement in engine maintenance ; 10% in inspection tasks). • **Complexity Scaling:** Benefits escalate as task complexity increases (e.g., piston pump systems) [2], [3]. • **Cost Impact:** Reduced downtime, decreased expert travel, and elimination of physical training assets [45], [64].	[2], [3], [7]
Quality & Error Reduction	• **Error Mitigation:** Visual overlays prevent mistakes. Reported 92.4% error reduction vs. paper manuals [22]. • **Precision:** Spatially correct 3D instructions prevent misalignment in assembly tasks [70]. • **Training Transfer:** Virtual practice leads to fewer errors during subsequent real-world execution [35].	[22], [31], [35], [70]
Learning & Knowledge Transfer	• **Risk-Free Practice:** VR enables "learning-by-doing" without equipment damage [10]. • **Retention:** Improved training permanency observed over 6-month periods [35]. • **Just-in-Time:** AR provides contextual knowledge directly at the point of need [42].	[10], [32], [35], [42], [77]
Human-Centric Advantages	• **Cognitive Load:** Reduces attention switching between manuals and tasks; aids processing in complex procedures [2], [16], [54]. • **Adaptability:** Content adapts to user skill levels (novice vs. expert) and preferences [42], [46], [76]. • **Ergonomics:** Hands-free operation via HMDs and voice assistants reduces physical strain [33], [62], [73].	[25], [42], [46], [54], [73], [76]
Collaboration & Safety	• **Remote Support:** Expert guidance for distributed teams; asynchronous collaboration on virtual prototypes [9], [13]. • **Hazard Awareness:** Visualization of safety zones (e.g., robot workspaces) and risk mitigation planning [19], [81].	[9], [13], [19], [28], [81]

Note: Where multiple references appear in a single cell, inline citations within the Key Benefits/Barriers column indicate the specific claim each reference supports. References listed in the Refs. column without inline attribution provide additional evidence for the category as a whole.

tasks. The visualization of 3D elements in their proper spatial context helps prevent misalignment and assembly errors.

3) Enhanced learning and knowledge transfer: XR technologies demonstrate significant benefits for maintenance training and knowledge transfer. VR creates safe environments for practice, eliminating risk to equipment and personnel. Study [10] explains that VR provides immersive simulations that enable learning-by-doing in risk-free settings, potentially shortening learning periods. Study [77] offers empirical evidence that VR-based training for wiring electric motors led to 10% faster task completion than traditional training.

AR facilitates learning directly within the work context, enabling just-in-time knowledge acquisition. Study [42] demonstrates that AR guidance enhances skill development by providing personalized instruction tailored to individual skill levels. Knowledge retention represents another advantage, as a study [35] reports improved training permanence with VR-based approaches, demonstrating sustained performance improvements over six months.

These XR learning benefits extend to knowledge sharing across organizations. Study [32] demonstrates how VR enhances collaboration and spatial understanding for globally distributed teams performing maintenance, documentation review, and risk assessment.

4) Human-centric advantages: Human-centric benefits address cognitive enhancement, ergonomic improvements, and personalized experiences. These advantages directly impact operator well-being and performance in maintenance contexts.

Cognitive Load Optimization: XR technologies effectively modulate cognitive load during complex procedures. Study [2] demonstrates that AR instructions enhance cognitive processing, particularly for complex tasks, by presenting information in a more intuitive and spatially relevant manner. Study [54] illustrates how AR reduces cognitive load through automatic object detection and spatial guidance, providing situation-aware and dynamic task assistance. Traditional maintenance approaches pose significant cognitive challenges, as highlighted in Study [16], which notes that operators must constantly shift their attention from the task at hand to instruction manuals, making disassembly processes error-prone and time-consuming. XR solutions address this fundamental limitation by overlaying contextual information directly onto the work environment, eliminating the need for attention switching and maintaining operator focus on the primary task.

Adaptability to User Characteristics: Approximately one-third of studies highlight personalization features that accommodate varying skill levels and learning styles. Study [76] presents an AR-based Adaptive Assistance System methodology that adapts content to user expertise level, adjusts information presentation based on preferences, and provides personalized assistance experiences. Study [42] demonstrates that AR can enhance the accessibility of manufacturing jobs by enabling personalized delivery of task information tailored to workers' preferences. Study [46] an adaptive framework for generating Augmented Reality (AR) instructions for machine operation, tailored to individual operators' skill levels. The system retrieves task data and worker profiles to provide personalized AR guidance, thereby improving productivity, safety, and worker satisfaction.

Ergonomic Enhancement: XR technologies contribute to improved physical ergonomics in many studies. Head-mounted AR displays enable hands-free operation, as demonstrated in study [33], allowing technicians to access information while maintaining physical engagement with equipment. Study [73] provides objective measurements showing AR instructions can reduce physical strain in certain muscle groups, particularly for simple maintenance tasks.

Improved Information Design: Enhanced information presentation is another human-centric advantage. Study [25] presents a methodology for converting technical documentation into AR-based manuals, optimizing text usage and converting textual instructions into visual elements. Study [62] shows how AR voice assistants can facilitate hands-free interaction during manual tasks, improving both ergonomics and information accessibility.

5) Collaboration and safety: Improved collaboration is reported in more than one-third of studies, with a particular emphasis on remote expert support. Study [9] demonstrates how AR assists service technicians with remote expert guidance for problems of varying difficulty. Study [13] illustrates how the COVE-VR platform facilitates asynchronous collaboration among globally distributed departments, enabling interaction with virtual prototypes in realistic settings.

Safety benefits manifest through risk-free training environments and improved hazard awareness. Study [28] proposes a human-centered conceptual model that integrates Augmented Reality (AR) and Dynamic Digital Models (DDM) to improve training and mitigate occupational risks in industrial contexts, enabling real-time risk management support for occupational safety. Study [81] presents a template concept for creating and modifying VR environments more efficiently in industrial contexts, specifically focusing on safety training for human-robot collaboration in industrial assembly. The approach emphasizes visualizing safety zones and robot workspaces while helping operators understand safety protocols. Study [19] presents a methodological proposal called SMART (Sistema Modular de Acceso Rápido Temporal) for implementing Virtual Reality (VR) and Augmented Reality (AR) systems to train engineering students in industrial maintenance and safety skills without exposing them to real risks. The methodology consists of four phases: Requirements, Architecture, Construction, and Evolution. The primary tasks involve utilizing VR for risk identification, assessment, and mitigation planning in industrial settings.

6) Evolution of advantages over time: The advantages of XR technologies have evolved significantly over the 2014-2025 review period, reflecting both technological advancements and a deeper understanding of their implementation.

Early studies (2014-2017) focused primarily on fundamental efficiency improvements and basic visualization capabilities. Study [22] exemplifies this phase, emphasizing the reduction of completion time and error elimination through AR visualization. Advantages described in this period tended to be directly measurable, such as time savings and error counts.

Middle-period research (2018-2021) expanded to include more sophisticated cognitive and learning benefits. Studies [10], [35], [47] demonstrate greater attention to knowledge transfer, cognitive support, and adaptive capabilities. The advantages described become more nuanced, addressing not just faster task completion but also enhanced understanding and knowledge retention.

Recent studies (2022-2025) show a shift toward personalization, human-centric design, and integration with other technologies. Study [75] demonstrates this trend by presenting an AR system that automatically generates task guidance using vision-language models, a level of integration with AI not seen in earlier studies. Study [70] showcases advanced MR applications that adapt to contextual awareness, while study [2] provides empirical evidence for AR's differential benefits based on task complexity.

This evolution reflects the maturation of XR from novel technical solutions to sophisticated sociotechnical systems that actively adapt to human needs and organizational contexts, suggesting continued development toward increasingly intelligent, integrated, and human-centered XR applications for industrial maintenance.

T. Limitations and Challenges of Extended Reality in Industrial Maintenance

The implementation of XR technologies in industrial maintenance faces several significant barriers that must be addressed to realize their full potential. Analysis of the primary studies reveals four major categories of limitations and challenges that currently impede wider adoption of these technologies.

1) Technical limitations: Hardware constraints represent the most frequently reported technical limitation. Head-mounted displays (HMDs) are particularly criticized for their limited field of view, which restricts the user's peripheral vision during maintenance tasks. Study [7] identifies this narrow field of view as problematic for guiding technicians during on-site repair tasks and providing remote experts with AR views of machinery for analysis. Battery life limitations also affect deployment feasibility, with study [15] highlighting the need for extended battery life to support all-day use in industrial settings.

Tracking and registration accuracy emerge as another significant technical challenge. Study [54] reports image distortion during rapid motion, which affects the reliability of object detection, and notes that current AR devices struggle with reflective or transparent objects common in industrial equipment. Registration misalignment, where virtual elements do not precisely align with physical components, is highlighted in studies [4], [36], [52], [59] as particularly problematic for maintenance tasks requiring high precision.

Network performance and computational requirements present additional technical barriers. Study [70] identifies limitations in network connectivity with current Wi-Fi technology as a constraint for data-intensive XR applications. Study [44] demonstrates these connectivity challenges in real-world field deployments, where poor network performance forced researchers to use dedicated 4G hotspots paired with HoloLens 2 devices to address connectivity issues, though even this solution proved insufficient for performance-intensive features that require high-bandwidth connections. Computational limitations identified across studies include processing complexity and performance constraints when handling large 3D CAD models [13], jitter in pose estimation algorithms [51], challenges in data management and scene reconstruction [71], and insufficient computational resources for complex scenarios requiring real-time processing and rendering.

2) Implementation and adoption barriers: Organizational implementation challenges appear in 42% of studies, spanning integration, acceptance, and resource constraints. The high implementation cost represents a significant barrier, particularly for small and medium enterprises. Studies [34], [64], [80] explicitly identify substantial initial investment requirements as a limitation, while study [29] points to financial resource constraints in adapting XR for technical training contexts.

User acceptance and adaptation difficulties are prominently reported in studies [9], [26], [35], [52], [59], [79]. Study [26] reports the need for user adaptation to symbol-based instructions in its proposed method, aiming to reduce the amount of text in technical documentation. Study [9] explicitly notes that resistance is present among technicians with lower technology-affinity scores. This reluctance manifests as skepticism about the accuracy and trustworthiness of information, with study [6] identifying potential trust issues in information provided through XR interfaces. Study [62] reports user frustration with speech recognition errors during maintenance tasks, highlighting the gap between expected and actual performance in real-world conditions.

Content-creation complexity poses a persistent challenge in implementation. Study [26] identifies the complexity of AR authoring as a significant barrier due to difficulties in creating scalable solutions for different types of maintenance manuals. Studies [47], [52] report the laborious model preparation required for effective AR implementation, thereby imposing a high threshold for initial deployment.

3) Human factors challenges: Cognitive and physical ergonomic issues are identified in 35% of studies. Extended use of HMDs can cause physical discomfort, with study [73] providing objective measurements showing increased strain in certain neck and shoulder muscles due to the weight and required posture of AR headsets. Study [3] reports the potential for cognitive overload due to focus rivalry between real and virtual information, particularly for complex tasks.

User skill variability presents challenges for designing appropriate XR interfaces. Study [40] identifies difficulties in providing proper guidance for users of varying skill levels, while study [3] notes a learning curve for novel AR interaction techniques. Study [55] reports initial challenges with gesture controls for users unfamiliar with AR interfaces.

Environmental considerations further complicate human factors design. Study [36] identifies implementation challenges related to varying lighting conditions, which affect tracking reliability. Study [20] notes the influence of humidity and temperature on sensing capabilities, while study [8] reports difficulties in detecting reflective or transparent objects when using Microsoft HoloLens smart glasses.

4) Methodological and evaluation challenges: Assessment limitations are also reported in the primary studies, particularly regarding the ecological validity of laboratory evaluations. Study [66] notes the difficulty in replicating real-world conditions in controlled tests and identifies challenges in balancing safety concerns with the requirements of real-world testing.

Many studies rely on limited sample sizes or non-representative participant groups. Study [76] acknowledges a key limitation in having only three inspectors test their ARAAS methodology, which potentially limits the generalizability of the results. Similarly, study [3] notes the limited generalizability of findings due to participant characteristics and the specific AR interface tested. Study [12] reports limited generalizability due to its focus on elevator maintenance, while presenting the xR Safety Kit framework for AR-based industrial maintenance solutions.

Long-term effectiveness evaluation remains particularly challenging. Study [17] identifies the need for studies examining extended XR use rather than single-session experiments. In contrast, study [3] notes limitations in understanding the long-term effects of AR use on user performance and adaptation.

These limitations and challenges, summarized in Table IV, highlight the current state of XR technologies in industrial maintenance as promising but still maturing. Many studies conclude with recommendations for future research that specifically target these barriers, suggesting a collective recognition of the need to address these challenges and advance the field toward more effective and widely implemented XR solutions.

U. Evaluation Criteria of XR in Industrial Maintenance

The systematic evaluation of XR technologies in industrial maintenance employs diverse criteria and instruments to validate effectiveness across multiple dimensions. Analysis of the primary studies reveals a structured evaluation landscape organized into five primary categories, as illustrated in Fig. 11, each addressing distinct aspects of XR system performance in maintenance contexts.

1) Performance-based evaluation: Objective performance metrics represent the most prevalent approach. Task completion time and error rates each appear in 25 studies, reflecting industrial emphasis on quantifiable operational improvements. Study [22] demonstrates AR's meaningful impact, reporting a 38% reduction in completion time and a 92.4% decrease in errors for motorcycle engine maintenance compared to paper instructions. Study [77] shows similar benefits for VR training, with 10% faster task completion for electric motor wiring. The combined assessment of efficiency (time) and effectiveness (errors) provides robust evidence for XR impact, as demonstrated across diverse maintenance scenarios in Studies [18], [36], [44].

2) Cognitive load and workload assessment: Cognitive evaluation appears in 16 studies, with the NASA Task Load Index used in 10 studies. This standardized questionnaire measures mental, physical, and temporal demands, as well as

TABLE IV. SUMMARY OF BARRIERS, LIMITATIONS, AND CHALLENGES IMPEDING XR ADOPTION IN INDUSTRIAL MAINTENANCE

Category	Key Barriers & Challenges	Refs.
Technical Limitations	• **Hardware Constraints:** Limited Field of View (FOV) restricts peripheral vision; battery life insufficient for full shifts [7], [15]. • **Tracking & Registration:** Misalignment of virtual overlays; instability with rapid movement or reflective/transparent surfaces [4]. • **Connectivity:** Wi-Fi/Network latency hinders data-intensive tasks; heavy processing of CAD models causes jitter [13], [70].	[4], [7], [13], [15], [70], [71]
Implementation & Adoption	• **Cost:** High initial investment and resource requirements for SMEs and training contexts . • **User Acceptance:** Resistance due to low tech affinity; trust issues with data accuracy; frustration with interaction errors (e.g., speech) [6], [9]. • **Content Creation:** Laborious model preparation and complex authoring processes create high deployment thresholds .	[6], [9]
Human Factors & Ergonomics	• **Physical Strain:** Neck/shoulder fatigue from HMD weight and prolonged posture . • **Cognitive Load:** Focus rivalry between real/virtual elements; cognitive overload in complex tasks . • **Environmental Sensitivity:** Lighting variations, humidity, and temperature affect sensor reliability and tracking .	[3], [8]
Methodological & Evaluation	• **Ecological Validity:** Difficulty replicating real-world industrial conditions (safety, chaos) in lab settings [66]. • **Generalizability:** Reliance on small sample sizes (e.g., N=3) or non-representative participant groups [12]. • **Longitudinal Data:** Lack of studies examining long-term effects, adaptation, and sustained performance [3], [17].	[3], [12], [17]

Note: Where multiple references appear in a single cell, inline citations within the Key Benefits/Barriers column indicate the specific claim each reference supports. References listed in the Refs. column without inline attribution provide additional evidence for the category as a whole.

performance, effort, and frustration. Study [2] reveals differential cognitive impact across task complexity, showing significant workload reduction for complex maintenance procedures, whereas simpler tasks yield minimal benefit. Study [3] extends this by measuring EEG (refers to the use of electroencephalography (EEG) to study and measure brain activity related to cognitive processes) during AR-assisted pump maintenance, revealing neural correlates of reduced cognitive demand. The integration of subjective workload measures with objective performance metrics provides complementary perspectives, as exemplified by the comprehensive evaluation of AR plant maintenance systems in Study citep7.

3) Physiological measurement: Physiological evaluation appears in 7 studies and offers unique insights through biosensing technologies. Heart rate variability emerges as the most common measure [2], [10] and assesses cardiovascular responses and physical stress. Electrodermal activity provides a complementary assessment of stress in Studies [4], [10]. Eye tracking offers particular value for evaluating visual attention and information processing; Study [4] employed comprehensive gaze behavior analysis during AR-assisted assembly, and Study [12] used it to identify safety hazards in VR simulations. Despite the advantages of continuous, real-time assessment and capture of unconscious responses, the relatively low adoption rate likely reflects practical constraints, including specialized equipment requirements and demands for technical expertise.

4) Usability and user experience: Usability assessment appears in 28 studies, emphasizing that technical functionality requires intuitive, satisfying user interactions. The System Usability Scale (SUS) emerges as the most widely adopted standardized instrument in 10 studies, enabling comparison across different XR implementations [15], [17], [54], [55]. User experience evaluation extends beyond narrow usability to encompass satisfaction and acceptance, appearing in 33 studies. Study [5] evaluates integration into existing maintenance workflows, while Study [11] focuses on perceived usefulness for industrial tasks. Several studies employ domain-specific instruments, such as ISONORM [7], which are tailored to industrial contexts and ergonomic standards.

5) Specialized dimensions and multi-method approaches: Learning outcomes are explicitly evaluated in 13 studies, particularly for VR training applications. Study [35] assesses six-month knowledge retention following VR-based assembly training and demonstrates sustained improvements in performance. Economic evaluation appears in 8 studies, with Study [64] quantifying the cost advantages of VR training through reduced training time and resources and its cost-effectiveness as a training solution. Safety assessment in 5 studies and collaboration quality in 5 studies address specialized application contexts.

A comprehensive evaluation employing multiple assessment modalities is reported in 18 studies. Study [4] exemplifies this approach, integrating five dimensions: task completion time, error analysis, NASA-TLX, physiological measures (EDA and inter-beat interval), and usability (PSSUQ). Study [7] evaluates effectiveness, efficiency, satisfaction, situational awareness (SART), and usability (ISONORM). This multi-method strategy enables the identification of potential trade-

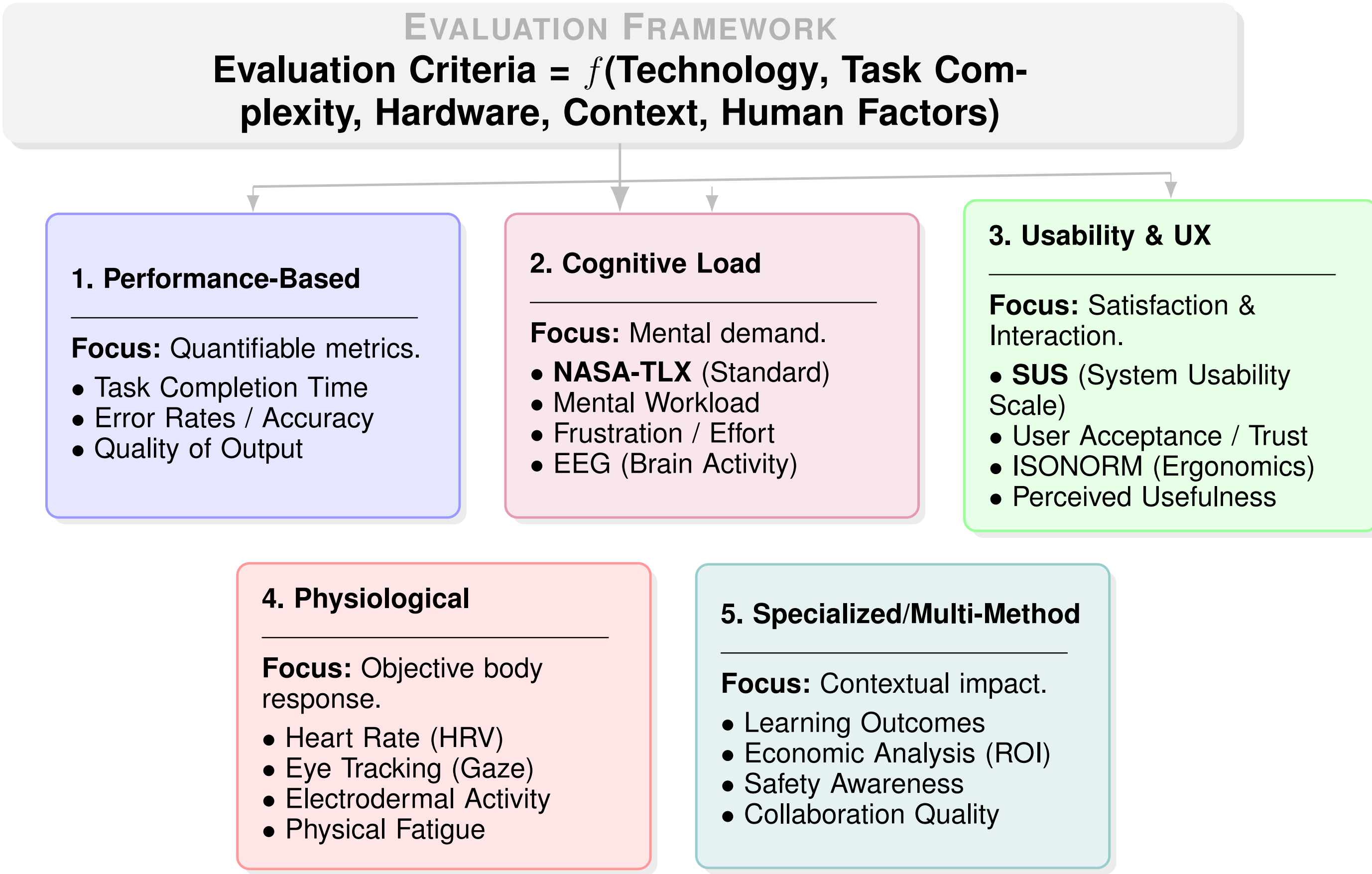

Fig. 11. Comprehensive evaluation framework for XR in industrial maintenance, illustrating the five primary assessment categories and the functional relationship defined in this review.

offs and provides both quantitative evidence and a nuanced understanding of user experiences.

6) Technology-specific patterns and framework: The relationship between evaluation approaches and implementation contexts reveals strategic patterns. Complex maintenance tasks require comprehensive evaluation, including cognitive load and physiological measures, as demonstrated in Studies [2], [3], [4]. Human-centric evaluation integration is featured in 42 studies, addressing cognitive support, ergonomics, adaptability, and user experience-critical factors for the adoption of industrial XR.

The comprehensive evaluation framework (see Fig. 11) illustrates the relationship: Evaluation Criteria = f(XR Technology, Task Complexity, Hardware, Application Area, Human-Centric Factors). This functional relationship informs the design of systematic evaluations, with criteria selection tailored to the type of technology (AR's operational focus suggests performance metrics; VR's training focus emphasizes learning outcomes), task complexity (complex scenarios justify using multiple methods), and human-centric factors (adaptive systems require assessing personalization effectiveness). As XR technologies advance and are adopted more widely, evaluation methods must also be developed to deliver strong evidence that supports confident industrial adoption decisions.

IV. Discussion

This systematic literature review synthesizes evidence from primary studies on extended reality (XR) technologies in industrial maintenance, revealing a rapidly maturing field transitioning from technology-centric implementations toward more sophisticated, human-centered systems.

A. Summary of Key Findings

The analysis reveals fundamental patterns in the adoption of XR for industrial maintenance. AR dominates current implementations (71.6%), primarily serving operational guidance and on-site assistance. VR accounts for 38.9% of studies, with strength in training and simulation contexts. MR represents only 6.3% but demonstrates emerging potential for collaborative maintenance scenarios. This distribution reflects pragmatic alignment between technology characteristics and maintenance task requirements.

Temporal analysis illuminates three distinct evolutionary phases. Early research (2014-2017) emphasized fundamental efficiency improvements through basic visualization. Middle-period studies (2018-2021) expanded to cognitive and learning benefits, incorporating adaptive capabilities and knowledge transfer mechanisms. Recent work (2022-2025) demonstrates AI integration, personalization, and context-aware systems with automatic content generation. This progression mirrors the transitions from Maintenance 4.0 to Maintenance 5.0, where human-centricity emerges as a central design principle.

The prominence of human-centric factors across 44.2% of studies signals an evolving research emphasis. Temporal analysis across the three identified phases supports this interpretation: human-centric factors appeared in approximately 25% of studies during Phase 1 (2014–2017), increased to 42% during Phase 2 (2018–2021), and reached 58% during Phase 3 (2022–2025). This progressive increase substantiates the characterization of a paradigm shift toward human-centered XR design in industrial maintenance. Evaluation approaches have matured, with 18.9% of studies employing comprehensive, multi-method assessments that integrate performance metrics, cognitive load measures, physiological indicators, and user experience dimensions.

B. Theoretical Contributions

This review presents two frameworks that advance the understanding of XR effectiveness in maintenance contexts.

The Evaluation Framework expresses effectiveness as a functional relationship: Evaluation Criteria = f(XR Technology, Task Complexity, Hardware, Application Area, Human-Centric Factors). This framework guides systematic assessment by recognizing that evaluation criteria must align with the characteristics of technology, task demands, and human factors. Complex maintenance procedures requiring AR guidance with HoloLens 2 in field deployments necessitate a comprehensive evaluation encompassing performance metrics, NASA-TLX cognitive assessment, usability measures, and physiological indicators. VR training applications require the measurement of learning outcomes, knowledge retention, and transfer effectiveness.

The Technology-Task-Context Alignment Model proposes optimal pairings between XR modalities, maintenance tasks, and operational contexts. AR demonstrates superiority for guidance, inspection, and procedural support in on-site environments where real-world context is essential. VR excels in training, planning, and simulating hazardous procedures in controlled learning environments. MR facilitates collaborative problem-solving and remote assistance in distributed work contexts. Misalignment produces suboptimal outcomes. Deploying VR for real-time repair introduces safety hazards, while using AR for initial skills training may impose an excessive cognitive load.

C. Comparison with Existing Literature

This review's findings both converge with and extend previous systematic reviews. Wang et al. [82] examined XR in product assembly, identifying similar temporal evolution patterns. However, their assembly focus revealed different technology distributions across workflow phases. In the pre-assembly phase, VR dominated pre-assembly activities, including training, simulation, and planning (30 VR versus 9 AR/MR implementations). Conversely, in the after-assembly phase encompassing maintenance activities, AR/MR showed clear dominance (30 AR/MR versus 8 VR implementations). This pattern aligns with the present review, where AR dominates operational maintenance guidance (57.9% of maintenance studies), highlighting how task characteristics shape technology selection.

Earlier maintenance-specific reviews established a foundational understanding at different maturity stages. Palmarini et al. [83] identified fragmented AR solutions and hardware limitations, concerns that remain partially relevant. Guo et al. [84] focused on VR applications across product lifecycles. Our findings extend these works by providing updated insights on AR hardware evolution, revealing recent VR acceleration post-2020, and documenting the emerging integration of AI and IoT.

The human-centric emphasis in our findings strongly supports the Maintenance 5.0 framework articulated by Psarommatis et al. [85], which expands beyond Industry 4.0's focus on automation and economic goals to encompass human-centricity, sustainability, and resilience. With 44.2% of studies addressing human-centric factors, our findings validate this paradigm shift toward systems that balance technological capability with human well-being, cognitive support, and sustainable operations.

Fang et al. [87] provided a comprehensive analysis of HMD AR in manufacturing, emphasizing the challenges of tracking, registration, and human-computer interaction. Our maintenance-focused analysis confirms these findings and reveals additional barriers, including the complexity of content authoring and the assessment of long-term effectiveness. The convergence among reviews on hardware limitations, registration accuracy, and human factors suggests fundamental rather than transient challenges.

Alam et al. [86] examined XR challenges in Industry 4.0 contexts, focusing on interoperability, adaptability, and cost barriers. Our findings corroborate these, while providing quantitative evidence: only 8.4% of studies included economic evaluation, suggesting systematic underattention to implementation costs in industrial decision-making.

D. Practical Implications

For industry practitioners, this review provides evidence-based guidance on selecting XR technology. Organizations should prioritize AR for procedural guidance and inspection, where demonstrated time reductions of 38% and error reductions of 92.4% provide clear value propositions. VR investments are justified for training applications, particularly for hazardous procedures where 10% efficiency improvements and enhanced knowledge retention offset development costs.

Implementation should follow staged approaches. Initial AR pilots targeting high-complexity maintenance with clear performance metrics enable value demonstration. Critical success factors include simplifying content authoring, robust change management that addresses user acceptance, and evaluation frameworks that capture both quantitative performance and qualitative user experience.

For XR system designers, human-centricity must be an architectural principle. Systems should incorporate adaptive capabilities that adjust to user expertise, task complexity, and environmental conditions. Multi-modal interaction, supporting both gesture and voice commands, accommodates diverse user preferences.

For researchers, this review identifies critical gaps. Longitudinal studies examining sustained XR usage beyond single-session experiments are urgently needed, as are standardized evaluation protocols enabling cross-study comparisons. Economic models incorporating the total cost of ownership would strengthen industrial adoption decisions. Physiological evaluation methods, currently employed by only 7.4% of studies, offer unique insights complementing traditional performance metrics.

E. Limitations

This review's scope and methodology impose limitations. Including assembly and disassembly tasks broadened the evidence base but may introduce heterogeneity, as assembly emphasizes different demands than traditional maintenance.

Grouping AR and MR reflects common practice but may mask important distinctions in system capabilities. Rapid technological change means findings regarding specific hardware platforms have limited temporal stability—limitations identified for 2015-era HMDs may not apply to current devices.

Most primary studies employed laboratory evaluations with students rather than field deployments with experienced technicians, limiting ecological validity. Small sample sizes and single-session designs restrict understanding of long-term effectiveness and adoption patterns. Publication bias toward positive results may overestimate the effectiveness of XR.

F. Future Research Directions

Immediate research priorities include longitudinal field studies examining XR adoption patterns and sustained usage in authentic industrial settings. Standardized evaluation frameworks would enable systematic comparison across implementations, facilitating meta-analyses. Economic evaluation incorporating comprehensive cost-benefit analyses would strengthen industrial decision-making.

Medium-term priorities should focus on integrating emerging technologies. AI-enhanced XR systems offering context-aware guidance, predictive maintenance support, and adaptive instruction are promising directions aligned with Maintenance 5.0 principles. Digital twin integration connecting XR interfaces with real-time equipment data could enable advanced diagnostic support and predictive capabilities. Multi-modal XR incorporating haptic feedback, spatial audio, and environmental sensing may improve training effectiveness.

Long-term research should examine the ethical implications of XR deployment. Questions regarding worker surveillance, skill deskilling versus augmentation, and equitable access require sustained attention. The development of XR systems that genuinely enhance human capabilities requires critical engagement with human-centered design principles and participatory development approaches.

This systematic literature review demonstrates that XR technologies have progressed beyond proof-of-concept to become viable tools for industrial maintenance. However, significant challenges remain before widespread adoption. Success requires continued attention to human factors, robust evaluation methodologies, and strategic implementation aligned with organizational capabilities and the characteristics of maintenance tasks.

V. Conclusion

This systematic literature review synthesizes evidence from 95 primary studies examining extended reality technologies in industrial maintenance, revealing a rapidly maturing field transitioning from technology-centric implementations toward human-centered systems aligned with Maintenance 5.0 principles. The analysis demonstrates that XR technologies have progressed beyond proof-of-concept to become viable tools that deliver measurable operational improvements while addressing the evolving complexity of modern industrial maintenance.

The research establishes three fundamental contributions. First, it identifies precise technology-task alignments: AR dominates operational guidance and real-time assistance (71.6% of studies), VR excels in training and simulation contexts (38.9%), while MR enables collaborative maintenance scenarios (6.3%). Second, temporal analysis reveals distinct evolutionary phases—from basic visualization (2014-2017), through cognitive enhancement (2018-2021), to AI-integrated adaptive systems (2022-2025)—mirroring the broader industrial transformation toward human-centric maintenance. Third, the prevalence of human-centric factors in 44.2% of studies signals a paradigm shift emphasizing cognitive support, ergonomics, adaptability, and user experience as central design considerations.

This review advances theoretical understanding through two frameworks. The Evaluation Framework expresses XR effectiveness as Evaluation Criteria = f(XR Technology, Task Complexity, Hardware, Application Area, Human-Centric Factors), providing systematic guidance for the design of assessments. The Technology-Task-Context Alignment Model recommends optimal pairings between XR modalities and maintenance requirements, acknowledging that misalignment yields suboptimal outcomes. These frameworks move beyond descriptive analysis to offer prescriptive guidance for implementation decisions.

Practical implications indicate AR investments should target high-complexity procedural guidance, where demonstrated time reductions of 38% and error reductions of 92.4% provide clear value propositions. VR deployment is justified for training applications, particularly those involving hazardous procedures, where the safety benefits and knowledge retention outweigh the development costs. Implementation success requires staged approaches, simplified content authoring, robust change management, and comprehensive evaluation frameworks.

However, these findings must be interpreted in light of persistent limitations. Most primary studies relied on laboratory evaluations with small sample sizes, limiting ecological validity and generalizability. Hardware constraints—including limited field of view, battery life, and tracking accuracy on reflective surfaces—remain unresolved barriers to industrial deployment. Content authoring complexity continues to impose high thresholds for initial adoption, and economic evaluation was addressed by only 8.4% of studies, leaving the cost-effectiveness of XR implementations insufficiently characterized. These observed limitations directly inform the most pressing research priorities. First, longitudinal field studies are needed to address the current reliance on single-session laboratory experiments identified across the reviewed literature. Second, standardized evaluation protocols would resolve the inconsistencies in assessment methodologies that currently prevent systematic cross-study comparison. Third, comprehensive economic models incorporating total cost of ownership would address the gap in financial analysis documented in this review. Beyond these immediate needs, future research should explore AI-enhanced adaptive systems, digital twin integration, and multi-modal interfaces, while engaging with the ethical implications of sustained XR deployment in industrial workplaces.

Credit Authorship Contribution Statement

Mouad Danane: Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

Abdelmajid Elouadi: Methodology, Validation, Supervision.

Youssef Rochdi: Conceptualization, Writing – review & editing.

Declaration of Generative AI and AI Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) used Claude AI (Anthropic) to improve the language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of Competing Interest

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

References

[1] Abidi, M. H., Ahmad, A., Darmoul, S., & Al-Ahmari, A. M. (2015). Haptics Assisted Virtual Assembly. *IFAC-PapersOnLine*, 48(3), 100–105. doi:10.1016/j.ifacol.2015.06.065

[2] Alessa, F. M., Alhaag, M. H., Al-harkan, I. M., Ramadan, M. Z., & Alqahtani, F. M. (2023). A Neurophysiological Evaluation of Cognitive Load during Augmented Reality Interactions in Various Industrial Maintenance and Assembly Tasks. *Sensors*, 23(18). doi:10.3390/s23187698

[3] Alessa, F. M., Alhaag, M. H., Al-harkan, I. M., Nasr, M. M., Kaid, H., & Hammami, N. (2024). Evaluating Physical Stress across Task Difficulty Levels in Augmented Reality-Assisted Industrial Maintenance. *Applied Sciences*, 14(1). doi:10.3390/app14010363

[4] Ariansyah, D., Erkoyuncu, J. A., Eimontaite, I., Johnson, T., Oostveen, A.-M., Fletcher, S., & Sharples, S. (2022). A Head Mounted Augmented Reality Design Practice for Maintenance Assembly: Toward Meeting Perceptual and Cognitive Needs of AR Users. *Applied Ergonomics*, 98, 103597. doi:10.1016/j.apergo.2021.103597

[5] Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., & Parkkinen, I. (2016). Use of Wearable and Augmented Reality Technologies in Industrial Maintenance Work. In *Proceedings of the International Academic Mindtrek Conference (AcademicMindtrek)* (pp. 235–242). Association for Computing Machinery. doi:10.1145/2994310.2994321

[6] Aromaa, S., Väätänen, A., Hakkarainen, M., & Kaasinen, E. (2018). User Experience and User Acceptance of an Augmented Reality Based Knowledge-Sharing Solution in Industrial Maintenance Work. In C. Falcao & T. Ahram (Eds.), *Advances in Intelligent Systems and Computing* (Vol. 607, pp. 145–156). Springer Verlag. doi:10.1007/978-3-319-60492-3_14

[7] Aschenbrenner, D., Latoschik, M. E., & Schillingz, K. (2016). Industrial Maintenance with Augmented Reality: Two Case Studies. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST)* (pp. 341–342). Association for Computing Machinery. doi:10.1145/2993369.2996305

[8] Bejczy, B., Bozyil, R., Vaičekauskas, E., Krogh Petersen, S. B., Bøgh, S., Hjorth, S. S., & Hansen, E. B. (2020). Mixed Reality Interface for Improving Mobile Manipulator Teleoperation in Contamination Critical Applications. *Procedia Manufacturing*, 51, 620–626. doi:10.1016/j.promfg.2020.10.087

[9] Bernsteiner, R., Ploder, C., Dilger, T., Nigg, J., Spieß, T., & Weichelt, R. (2021). An Analysis of an Augmented Reality Application to Support Service Staff in Industrial Maintenance. In L. Uden, I. Ting, & K. Wang (Eds.), *Communications in Computer and Information Science* (Vol. 1438, pp. 457–467). Springer. doi:10.1007/978-3-030-81635-3_37

[10] Brunzini, A., Grandi, F., Peruzzini, M., & Pellicciari, M. (2021). Virtual Training for Assembly Tasks: A Framework for the Analysis of the Cognitive Impact on Operators. *Procedia Manufacturing*, 55, 527–534. doi:10.1016/j.promfg.2021.10.072

[11] Burova, A., Heinonen, H., Palma, P. B., Keskinen, T., Hakulinen, J., Opas, V., Mäkela, J., Ronkainen, K., Siltanen, S., Raisamo, R., & Turunen, M. (2021). Toward Efficient Academia-Industry Collaboration: A Case Study of Joint VR System Development. In *ACM International Conference Proceeding Series* (pp. 176–185). Association for Computing Machinery. doi:10.1145/3464327.3464367

[12] Burova, A., Mäkela, J., Hakulinen, J., Keskinen, T., Heinonen, H., Siltanen, S., & Turunen, M. (2020). Utilizing VR and Gaze Tracking to Develop AR Solutions for Industrial Maintenance. In *Proceedings of the Conference on Human Factors in Computing Systems (CHI)*. Association for Computing Machinery. doi:10.1145/3313831.3376405

[13] Burova, A., Mäkela, J., Heinonen, H., Palma, P. B., Hakulinen, J., Opas, V., Siltanen, S., Raisamo, R., & Turunen, M. (2022). Asynchronous Industrial Collaboration: How Virtual Reality and Virtual Tools Aid the Process of Maintenance Method Development and Documentation Creation. *Computers in Industry*, 140. doi:10.1016/j.compind.2022.103663

[14] Burova, A., Palma, P. B., Truong, P., Mäkela, J., Heinonen, H., Hakulinen, J., Ronkainen, K., Raisamo, R., Turunen, M., & Siltanen, S. (2022). Distributed Asymmetric Virtual Reality in Industrial Context: Enhancing the Collaboration of Geographically Dispersed Teams in the Pipeline of Maintenance Method Development and Technical Documentation Creation. *Applied Sciences*, 12(8). doi:10.3390/app12083728

[15] Cachada, A., Romero, L., Costa, D., Badikyan, H., Barbosa, J., Leitao, P., Morais, O., Teixeira, C., Azevedo, J., & Moreira, P. M. (2019). Using AR Interfaces to Support Industrial Maintenance Procedures. In *Proceedings of IECON* (pp. 3795–3800). IEEE. doi:10.1109/IECON.2019.8927815

[16] Chang, M. M. L., Ong, S. K., & Nee, A. Y. C. (2017). AR-Guided Product Disassembly for Maintenance and Remanufacturing. *Procedia CIRP*, 61, 299–304. doi:10.1016/j.procir.2016.11.194

[17] Daling, L. M., Tenbrock, M., Isenhardt, I., & Schlittmeier, S. J. (2023). Assemble It like This! – Is AR- or VR-Based Training an Effective Alternative to Video-Based Training in Manual Assembly? *Applied Ergonomics*, 110, 104021. doi:10.1016/j.apergo.2023.104021

[18] De Pace, F., Manuri, F., Sanna, A., & Zappia, D. (2019). Corrigendum: A Comparison Between Two Different Approaches for a Collaborative Mixed-Virtual Environment in Industrial Maintenance. *Frontiers in Robotics and AI*, 6. doi:10.3389/frobt.2019.00051

[19] Elia, V., Gnoni, M. G., & Lanzilotto, A. (2016). Evaluating the Application of Augmented Reality Devices in Manufacturing from a Process Point of View: An AHP Based Model. *Expert Systems with Applications*, 63, 187–197. doi:10.1016/j.eswa.2016.07.006

[20] Erkoyuncu, J., & Khan, S. (2020). Olfactory-Based Augmented Reality Support for Industrial Maintenance. *IEEE Access*, 8, 30306–30321. doi:10.1109/ACCESS.2020.2970220

[21] Erkoyuncu, J. A., del Amo, I. F., Dalle Mura, M., Roy, R., & Dini, G. (2017). Improving Efficiency of Industrial Maintenance with Context Aware Adaptive Authoring in Augmented Reality. *CIRP Annals - Manufacturing Technology*, 66(1), 465–468. doi:10.1016/j.cirp.2017.04.006

[22] Fiorentino, M., Uva, A. E., Gattullo, M., Debernardis, S., & Monno, G. (2014). Augmented Reality on Large Screen for Interactive Maintenance Instructions. *Computers in Industry*, 65(2), 270–278. doi:10.1016/j.compind.2013.11.004

[23] Flotyński, J., Walczak, K., Sobociński, P., & Gałązkiewicz, A. (2021). Knowledge-Based Management of Virtual Training Scenarios. *Procedia Computer Science*, 192, 766–775. doi:10.1016/j.procs.2021.08.079

[24] Freddi, M., & Frizziero, L. (2020). Design for Disassembly and Augmented Reality Applied to a Tailstock. *Actuators*, 9(4), 1–14. doi:10.3390/act9040102

[25] Gattullo, M., Scurati, G. W., Fiorentino, M., Uva, A. E., Ferrise, F., & Bordegoni, M. (2019). Towards Augmented Reality Manuals for Industry 4.0: A Methodology. *Robotics and Computer-Integrated Manufacturing*, 56, 276–286. doi:10.1016/j.rcim.2018.10.001

[26] Gattullo, M., Uva, A. E., Fiorentino, M., Scurati, G. W., & Ferrise, F. (2017). From Paper Manual to AR Manual: Do We Still Need Text? *Procedia Manufacturing*, 11, 1303–1310. doi:10.1016/j.promfg.2017.07.258

[27] Gong, Y., Su, C., & Wei, Y. (2019). An Interactive Task Modeling Method for the Development of Augmented Reality Maintenance Guiding System. In *Proceedings of the International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMSC)* (Vol. 1, pp. 136–140). IEEE. doi:10.1109/IHMSC.2019.00039

[28] Gualtieri, L., Revolti, A., & Dallasega, P. (2023). A Human-Centered Conceptual Model for Integrating Augmented Reality and Dynamic Digital Models to Reduce Occupational Risks in Industrial Contexts. *Procedia Computer Science*, 217, 765–773. doi:10.1016/j.procs.2022.12.273

[29] Guler, O., & Yucedag, I. (2018). Developing an CNC Lathe Augmented Reality Application for Industrial Maintanance Training. In *Proceedings of the International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*. IEEE. doi:10.1109/ISMSIT.2018.8567255

[30] Hassan, M., Montague, G., Iqbal, M. Z., & Fahey, J. (2024). Virtual Reality-Based Bioreactor Digital Twin for Operator Training. *Digital Chemical Engineering*, 11, 100147. doi:10.1016/j.dche.2024.100147

[31] Havard, V., Baudry, D., Savatier, X., Jeanne, B., Louis, A., & Mazari, B. (2016). Augmented Industrial Maintenance (AIM): A Case Study for Evaluating and Comparing with Paper and Video Media Supports. In L.T. De Paolis & A. Mongelli (Eds.), *Lecture Notes in Computer Science* (Vol. 9768, pp. 302–320). Springer Verlag. doi:10.1007/978-3-319-40621-3_22

[32] Heinonen, H., Burova, A., Siltanen, S., Lähteenmäki, J., Hakulinen, J., & Turunen, M. (2022). Evaluating the Benefits of Collaborative VR Review for Maintenance Documentation and Risk Assessment. *Applied Sciences*, 12(14). doi:10.3390/app12147155

[33] Heinz, M., Dhiman, H., & Röcker, C. (2018). A Multi-Device Assistive System for Industrial Maintenance Operations. In *Lecture Notes in Computer Science* (Vol. 11015, pp. 239–247). Springer Verlag. doi:10.1007/978-3-319-99740-7_16

[34] Isik, B., Isik, G. E., & Zilka, M. (2024). Integrating Extended Reality in Industrial Maintenance: A Game-Based Framework for Compressed Air System Training. In *Procedia Computer Science* (Vol. 232, pp. 483–492). Elsevier B.V. doi:10.1016/j.procs.2024.01.048

[35] Kalkan, Ö. K., Karabulut, Ş., & Höke, G. (2021). Effect of Virtual Reality-Based Training on Complex Industrial Assembly Task Performance. *Arabian Journal for Science and Engineering*, 46(12), 12697–12708. doi:10.1007/s13369-021-06138-w

[36] Laviola, E., Gattullo, M., Evangelista, A., Fiorentino, M., & Uva, A. E. (2023). In-Situ or Side-by-Side? A User Study on Augmented Reality Maintenance Instructions in Blind Areas. *Computers in Industry*, 144, 103795. doi:10.1016/j.compind.2022.103795

[37] Leutert, F., & Schilling, K. (2018). Projector-Based Augmented Reality for Telemaintenance Support. *IFAC-PapersOnLine*, 51(11), 502–507. doi:10.1016/j.ifacol.2018.08.368

[38] Liu, C., Zhu, H., Tang, D., Nie, Q., Zhou, T., Wang, L., & Song, Y. (2022). Probing an Intelligent Predictive Maintenance Approach with Deep Learning and Augmented Reality for Machine Tools in IoT-Enabled Manufacturing. *Robotics and Computer-Integrated Manufacturing*, 77, 102357. doi:10.1016/j.rcim.2022.102357

[39] Loch, F., Ziegler, U., & Vogel-Heuser, B. (2018). Integrating Haptic Interaction into a Virtual Training System for Manual Procedures in Industrial Environments. *IFAC-PapersOnLine*, 51(11), 60–65. doi:10.1016/j.ifacol.2018.08.235

[40] Loch, F., Ziegler, U., & Vogel-Heuser, B. (2019). Using Real-Time Feedback in a Training System for Manual Procedures. *IFAC-PapersOnLine*, 52(19), 241–246. doi:10.1016/j.ifacol.2019.12.089

[41] Mei, Y., Liu, Y., Sun, C., Wang, X., Wang, D., Yuan, L., & Tan, J. (2023). Multi-Stage Rotors Assembly of Turbine-Based Combined Cycle Engine Based on Augmented Reality. *Advanced Engineering Informatics*, 58, 102160. doi:10.1016/j.aei.2023.102160

[42] Moghaddam, M., Wilson, N. C., Modestino, A. S., Jona, K., & Marsella, S. C. (2021). Exploring Augmented Reality for Worker Assistance versus Training. *Advanced Engineering Informatics*, 50, 101410. doi:10.1016/j.aei.2021.101410

[43] Mompeu, G., Danglade, F., Mérienne, F., & Guillet, C. (2024). Methodology for Augmented Reality-Based Adaptive Assistance in Industry. *Computers in Industry*, 154, 104021. doi:10.1016/j.compind.2023.104021

[44] Monetti, F. M., de Giorgio, A., Yu, H., Maffei, A., & Romero, M. (2022). An Experimental Study of the Impact of Virtual Reality Training on Manufacturing Operators on Industrial Robotic Tasks. *Procedia CIRP*, 106, 33–38. doi:10.1016/j.procir.2022.02.151

[45] Mourtzis, D., Angelopoulos, J., & Boli, N. (2018). Maintenance Assistance Application of Engineering to Order Manufacturing Equipment: A Product Service System (PSS) Approach. *IFAC-PapersOnLine*, 51(11), 217–222. doi:10.1016/j.ifacol.2018.08.263

[46] Mourtzis, D., Xanthi, F., & Zogopoulos, V. (2019). An Adaptive Framework for Augmented Reality Instructions Considering Workforce Skill. *Procedia CIRP*, 81, 363–368. doi:10.1016/j.procir.2019.03.063

[47] Mura, M. D., & Dini, G. (2021). A Proposal of an Assembly Workstation for Car Panel Fitting Aided by an Augmented Reality Device. *Procedia CIRP*, 103, 225–230. doi:10.1016/j.procir.2021.10.036

[48] Neges, M., Adwernat, S., & Abramovici, M. (2018). Augmented Virtuality for Maintenance Training Simulation under Various Stress Conditions. *Procedia Manufacturing*, 19, 171–178. doi:10.1016/j.promfg.2018.01.024

[49] Numfu, M., Riel, A., & Noël, F. (2020). A Concept for Virtual Reality Based Industrial Maintenance Training Preparation. In *Communications in Computer and Information Science* (Vol. 1251, pp. 820–829). Springer. doi:10.1007/978-3-030-56441-4_62

[50] Numfu, M., Riel, A., & Noel, F. (2019). Virtual Reality Based Digital Chain for Maintenance Training. *Procedia CIRP*, 84, 1069–1074. doi:10.1016/j.procir.2019.04.268

[51] Ortega, M., Ivorra, E., Juan, A., Venegas, P., Martínez, J., & Alcañiz, M. (2021). Mantra: An Effective System Based on Augmented Reality and Infrared Thermography for Industrial Maintenance. *Applied Sciences*, 11(1), 1–26. doi:10.3390/app11010385

[52] Osti, F., Ceruti, A., Liverani, A., & Caligiana, G. (2017). Semi-Automatic Design for Disassembly Strategy Planning: An Augmented Reality Approach. *Procedia Manufacturing*, 11, 1481–1488. doi:10.1016/j.promfg.2017.07.279

[53] Oulefki, A., Himeur, Y., Trongtirakul, T., Amara, K., Agaian, S., Benbelkacem, S., Guerroudji, M. A., Zemmouri, M., Ferhat, S., Zenati, N., Atalla, S., & Mansoor, W. (2024). Detection and Analysis of Deteriorated Areas in Solar PV Modules Using Unsupervised Sensing Algorithms and 3D Augmented Reality. *Heliyon*, 10(6), e27973. doi:10.1016/j.heliyon.2024.e27973

[54] Park, K.-B., Kim, M., Choi, S. H., & Lee, J. Y. (2020). Deep Learning-Based Smart Task Assistance in Wearable Augmented Reality. *Robotics and Computer-Integrated Manufacturing*, 63, 101887. doi:10.1016/j.rcim.2019.101887

[55] Quandt, M., Beinke, T., & Freitag, M. (2020). User-Centered Evaluation of an Augmented Reality-Based Assistance System for Maintenance. *Procedia CIRP*, 93, 921–926. doi:10.1016/j.procir.2020.03.053

[56] Richard, K., Havard, V., His, J., & Baudry, D. (2021). INTERVALES: INTERactive Virtual and Augmented Framework for industriaL Environment and Scenarios. *Advanced Engineering Informatics*, 50, 101425. doi:10.1016/j.aei.2021.101425

[57] Ritucci, A. L., Frizziero, L., & Liverani, A. (2021). Maintainability Approach: Hydraulic Pump with External Gears Explored with Design for Disassembly and Augmented Reality. *Applied Sciences*, 11(2), 1–23. doi:10.3390/app11020666

[58] Sanna, A., Manuri, F., Piumatti, G., Paravati, G., Lamberti, F., & Pezzolla, P. (2015). A Flexible AR-Based Training System for Industrial Maintenance. In *Lecture Notes in Computer Science* (Vol. 9254, pp. 314–331). Springer Verlag. doi:10.1007/978-3-319-22888-4_23

[59] Sattarpanah Karganroudi, S., Silva, R. E., Chahdi El Ouazani, Y., Aminzadeh, A., Dimitrova, M., & Ibrahim, H. (2022). A Novel Assembly Process Guidance Using Augmented Reality for a Standalone Hybrid Energy System. *The International Journal of Advanced Manufacturing Technology*, 122(7–8), 3425–3445. doi:10.1007/s00170-022-10122-5

[60] Schlagowski, R., Merkel, L., & Meitinger, C. (2017). Design of an Assistant System for Industrial Maintenance Tasks and Implementation of a Prototype Using Augmented Reality. In *Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 294–298). IEEE. doi:10.1109/IEEM.2017.8289899

[61] Scurati, G. W., Gattullo, M., Fiorentino, M., Ferrise, F., Bordegoni, M., & Uva, A. E. (2018). Converting Maintenance Actions into Standard Symbols for Augmented Reality Applications in Industry 4.0. *Computers in Industry*, 98, 68–79. doi:10.1016/j.compind.2018.02.001

[62] Serras, M., Garcia-Sardina, L., Simoes, B., Alvarez, H., & Arambarri, J. (2020). AREVA: Augmented Reality Voice Assistant for Industrial Maintenance. *Procesamiento del Lenguaje Natural*, 65, 135–138. doi:10.26342/2020-65-21

[63] Shamsuzzoha, A., Helo, P., Kankaanpää, T., Toshev, R., & Tuan, V. V. (2018). Applications of Virtual Reality in Industrial Repair and Maintenance. In *Proceedings of the International Conference on Industrial Engineering and Operations Management* (pp. 1890–1898). IEOM Society.

[64] Shamsuzzoha, A., Toshev, R., Vu Tuan, V., Kankaanpaa, T., & Helo, P. (2021). Digital Factory–Virtual Reality Environments for Industrial Training and Maintenance. *Interactive Learning Environments*, 29(8), 1339–1362. doi:10.1080/10494820.2019.1628072

[65] Siew, C. Y., Nee, A. Y. C., & Ong, S. K. (2019). Improving Maintenance Efficiency with an Adaptive AR-Assisted Maintenance System. In *ACM International Conference Proceeding Series* (pp. 74–78). Association for Computing Machinery. doi:10.1145/3351180.3351203

[66] Talami, F., de Barros, A., Silva, P., Vasconcelos, A., & Santos, G. (2023). AR in Remote Maintenance: Empirical User Research with Dyads. In *IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* (pp. 425–431). IEEE. doi:10.1109/VRW58643.2023.00092

[67] Tripicchio, P., Avizzano, C. A., & Bergamasco, M. (2019). A 6-DOF Haptic Manipulation System to Verify Assembly Procedures on CAD Models. *Procedia Manufacturing*, 38, 1292–1299. doi:10.1016/j.promfg.2020.01.161

[68] Wang, Z., Zhang, X., Li, L., Zhou, Y., Lu, Z., Dai, Y., Liu, C., Su, Z., Bai, X., & Billinghurst, M. (2023). Evaluating Visual Encoding Quality of a Mixed Reality User Interface for Human–Machine Co-Assembly in Complex Operational Terrain. *Advanced Engineering Informatics*, 58, 102171. doi:10.1016/j.aei.2023.102171

[69] Weltin, M., Lucke, D., & Jooste, J. L. (2023). Automatic Content Creation System for Augmented Reality Maintenance Applications for Legacy Machines. *Procedia CIRP*, 120, 750–755. doi:10.1016/j.procir.2023.09.070

[70] Zhang, X., Bai, X., Zhang, S., He, W., Wang, S., Yan, Y., & Wang, P., Liu, L. (2024). A Novel Mixed Reality Remote Collaboration System with Adaptive Generation of Instructions. *Computers & Industrial Engineering*, 110353. doi:10.1016/j.cie.2024.110353

[71] Zhang, X., Bai, X., Zhang, S., He, W., Wang, S., Yan, Y., Yu, Q., & Liu, L. (2023). A Novel MR Remote Collaboration System Using 3D Spatial Area Cue and Visual Notification. *Journal of Manufacturing Systems*, 67, 389–409. doi:10.1016/j.jmsy.2023.02.013

[72] Zheng, L., Liu, X., An, Z., Li, S., & Zhang, R. (2020). A Smart Assistance System for Cable Assembly by Combining Wearable Augmented Reality with Portable Visual Inspection. *Virtual Reality & Intelligent Hardware*, 2(1), 12–27. doi:10.1016/j.vrih.2019.12.002

[73] Velosa, J. D., Cobo, L., Castillo, F., & Castillo, C. (2018). Methodological Proposal for Use of Virtual Reality VR and Augmented Reality AR in the Formation of Professional Skills in Industrial Maintenance and Industrial Safety. In *Lecture Notes in Networks and Systems* (Vol. 22, pp. 987–1000). Springer. doi:10.1007/978-3-319-64352-6_92

[74] Nagy, A., Spyridis, Y., Mills, G. J., & Argyriou, V. (2024). User Experience Evaluation of AR Assisted Industrial Maintenance and Support Applications. In *Proceedings of the International Conference on Virtual Reality (ICVR)* (pp. 270–277). doi:10.1109/ICVR62393.2024.10869099

[75] Stover, D., & Bowman, D. (2024). TAGGAR: General-Purpose Task Guidance from Natural Language in Augmented Reality Using Vision-Language Models. doi:10.1145/3677386.3682095

[76] Mompeu, G., Danglade, F., Mérienne, F., & Guillet, C. (2024). Methodology for Augmented Reality-Based Adaptive Assistance in Industry. *Computers in Industry*, 154, 104021. doi:10.1016/j.compind.2023.104021

[77] Obermair, F., Althaler, J., Wolfartsberger, J., Niedermayr, D., & Feichtenschlager, H.-P. (2024). Assembly Training for Electric Motor Wiring with Virtual Reality Compared to Paper Instructions: Experiment and Analysis. *Procedia CIRP*, 130, 398–406. doi:10.1016/j.procir.2024.10.106

[78] Padovano, A., Cardamone, M., & Klaess, J. (2024). Empowering Operator 5.0: Human-Centric Design of an Augmented Reality Tool for a Learning Factory. In *6th IFAC Workshop on Advanced Maintenance Engineering, Services and Technology (AMEST)* (Vol. 58, pp. 180–185). doi:10.1016/j.ifacol.2024.08.117

[79] Costa, A., Miranda, J., Dias, D., Dinis, N., Romero, L., Faria, P. M., Smart Maintenance Solutions: AR- and VR-Enhanced Digital Twin Powered by FIWARE, *Sensors*, 25(3), 2025. doi:10.3390/s25030845.

[80] Işık, B., Işık, G. E., Zilka, M., Game-Based Learning for Industrial Maintenance: A Unity 3D Educational Game of Compressed Air System Training, *Procedia Computer Science*, 253, 784–793, 2025. doi:10.1016/j.procs.2025.01.140.

[81] Dianatfar, M., Järvenpää, E., Siltala, N., Lanz, M., Template Concept for VR Environments: A Case Study in VR-Based Safety Training for Human–Robot Collaboration, *Robotics and Computer-Integrated Manufacturing*, 94, 102973, 2025. doi:10.1016/j.rcim.2025.102973.

[82] Wang, B., Zheng, L., Wang, Y., Fang, W., Wang, L., Towards the industry 5.0 frontier: Review and prospect of XR in product assembly, *Journal of Manufacturing Systems*, 74, 777–811, 2024. doi:10.1016/j.jmsy.2024.05.002.

[83] Palmarini, R., Erkoyuncu, J. A., Roy, R., Torabmostaedi, H., A systematic review of augmented reality applications in maintenance, *Robotics and Computer-Integrated Manufacturing*, 49, 215–228, 2018. doi:10.1016/j.rcim.2017.06.002.

[84] Guo, Z., Zhou, D., Zhou, Q., Zhang, X., Geng, J., Zeng, S., Lv, C., Hao, A., Applications of virtual reality in maintenance during the industrial product lifecycle: A systematic review, *Journal of Manufacturing Systems*, 56, 525–538, 2020. doi:10.1016/j.jmsy.2020.07.007.

[85] Psarommatis, F., May, G., Azamfirei, V., Envisioning maintenance 5.0: Insights from a systematic literature review of Industry 4.0 and a proposed framework, *Journal of Manufacturing Systems*, 68, 376–399, 2023. doi:10.1016/j.jmsy.2023.04.009.

[86] Alam, N., Saha, N., Gadow, V., Harik, R., Ryu, J., Role of extended reality (XR) technologies in maintenance operations: Trends, challenges, and integration in industry 4.0, *Manufacturing Letters*, 44, 1545–1557, 2025. doi:10.1016/j.mfglet.2025.06.174.

[87] Fang, W., Chen, L., Zhang, T., Chen, C., Teng, Z., Wang, L., Head-mounted display augmented reality in manufacturing: A systematic review, *Robotics and Computer-Integrated Manufacturing*, 83, 102567, 2023. doi:10.1016/j.rcim.2023.102567.

[88] Esmaeilian, B., Behdad, S., Wang, B., The evolution and future of manufacturing: A review, *Journal of Manufacturing Systems*, 39, 79–100, 2016.

[89] Salawu, E. Y., Awoyemi, O. O., Akerekan, O. E., Afolalu, S. A., Kayode, J. F., Ongbali, S. O., Airewa, I., Edun, B. M., Impact of maintenance on machine reliability: A review, In *E3S Web of Conferences*, 430, 01226, 2023. EDP Sciences.

[90] Achouch, M., Dimitrova, M., Ziane, K., Sattarpanah Karganroudi, S., Dhouib, R., Ibrahim, H., Adda, M., On predictive maintenance in industry 4.0: Overview, models, and challenges, *Applied Sciences*, 12(16), 8081, 2022. MDPI.

[91] Zonta, T., Da Costa, C. A., da Rosa Righi, R., de Lima, M. J., Da Trindade, E. S., Li, G. P., Predictive maintenance in the Industry 4.0: A systematic literature review, *Computers & Industrial Engineering*, 150, 106889, 2020. Elsevier.

[92] Nahavandi, S., Industry 5.0—A human-centric solution, *Sustainability*, 11(16), 4371, 2019. MDPI.

[93] Casini, M., Extended reality for smart building operation and maintenance: A review, *Energies*, 15(10), 3785, 2022. MDPI.

[94] Coupry, C., Noblecourt, S., Richard, P., Baudry, D., Bigaud, D., BIM-Based digital twin and XR devices to improve maintenance procedures in smart buildings: A literature review, *Applied Sciences*, 11(15), 6810, 2021. MDPI.

[95] Yazdi, M., Augmented reality (AR) and virtual reality (VR) in maintenance training, In *Advances in Computational Mathematics for Industrial System Reliability and Maintainability*, 169–183, 2024. Springer.