frontiers in Virtual Reality

TYPE Systematic Review
PUBLISHED 10 April 2026
DOI 10.3389/frvir.2026.1797341

EDITED BY
Amela Sadagic,
Naval Postgraduate School, United States

REVIEWED BY
Daniel Rene Mestre,
Aix-Marseille Université, France
Etienne Gernez,
Oslo School of Architecture and Design,
Norway

*CORRESPONDENCE
Joni Rajamäki,
✉ joni.rajamaki@utu.fi

RECEIVED 27 January 2026
REVISED 05 March 2026
ACCEPTED 13 March 2026
PUBLISHED 10 April 2026

CITATION
Rajamäki J, Tapola M, Heimo O, Lehtonen T and Järvi J (2026) Applications of extended reality within the shipbuilding industry: a systematic literature review. *Front. Virtual Real.* 7:1797341.
doi: 10.3389/frvir.2026.1797341

Applications of extended reality within the shipbuilding industry: a systematic literature review

Joni Rajamäki*, Mirva Tapola, Olli Heimo, Teijo Lehtonen and Jaakko Järvi

Department of Computing, University of Turku, Turku, Finland

Extended reality includes virtual reality which places the user into a virtual world and augmented reality which adds virtual elements to the real world. Extended reality has been touted as a pivotal technology as part of industry 4.0, but has yet to make a significant impact in industrial applications. Shipbuilding is a longstanding and traditional branch of industry which is characterized as slow to innovate. The importance of shipbuilding is rising as regions like the arctic are being unlocked and as a result additional demand is placed onto shipyards. In order to better accommodate increased demands, novel means for better efficiency are welcomed within shipbuilding. This article presents a systematic literature review analyzing the research in the use of extended reality within the shipbuilding industry. The focuses of this review are on the current extent of research being conducted, how different sub technologies of extended reality overlap with different phases of shipbuilding, and how technology is evaluated and what kind of value can be derived from current research. A total of 44 articles from nine sources are reviewed. The results indicate an overall early state of research characterized by a heavy focus on pilot research. Clear use cases for extended reality solutions are identified and some instances of demonstrable value for shipbuilding operations are presented. Shortcomings in the current research and potential future directions are also outlined.

KEYWORDS
augmented reality, extended reality, shipbuilding, systematic literature review, virtual reality

1 Introduction

Extended reality (XR) refers to immersive technologies that either place the user into a virtual world or add virtual elements to the real world surroundings of the user. Full digital immersion is referred to as *virtual reality* (VR), while the addition of virtual elements to the real world is called *augmented reality* (AR). Major manufacturers such as Apple and Microsoft have been developing and marketing their XR platforms as productivity tools for professional use (Apple, 2025; Microsoft, 2024) for quite some time. Yet XR technologies have not found broad adoption in an industrial context. Their use today is still mostly limited to niche user demographics in entertainment (Valente et al., 2018) and teaching (Samala et al., 2024).

According to *Diffusion of Innovation* theory (Rogers, 1962), technology spreads through social systems non-linearly. A certain critical mass is necessary for the diffusion of technology, and therefore industrial applications are crucial for the wider adoption and spreading of emergent technologies. Successfully deploying a novel technology in an industrial setting gives validity to the subject matter within and across organizations

(Ren, 2019). In this paper we examine the adoption of XR technologies within shipbuilding, a traditional and regulated industry that is known to be conservative in adopting new technologies. It is these characteristics that make the shipbuilding industry an interesting target for studying the adopting of the emerging technology of XR.

Shipbuilding is a historic and longstanding branch of industry. Early signs of ship remains can be dated back to 5,000–6000 B.C (Carter, 2006). On the one hand, these historic roots are visible in today's shipbuilding; the industry is traditionally slow in innovating and adopting new technologies (Makkonen et al., 2013; Sánchez-Sotano et al., 2020). On the other hand, the modern shipbuilding industry is challenged to innovate faster: shipyards are in a fierce global competition, and demands for more sustainable building and operating of ships are getting louder. Novel technologies that can improve efficiency in shipbuilding are welcomed.

XR technologies are not yet in widespread use in practice in shipbuilding, and research into XR applications within the this industry is limited and fragmented. Even the terminology for the use of XR technology within shipbuilding is not standard. For instance, Choi and Seo use the term "AR" when employing markers for external cameras in their research of ship block assembly progress tracking (Choi and Seo, 2020), while other authors use the same term to describe solutions based on head mounted devices (HMD) (Chen et al., 2021). Further, the technology landscape pertaining to XR is evolving rapidly, which results in short life cycles for both technologies and research results. As an example; Fraga-Lamas et al. in their 2018 review of industrial augmented reality recommend against the usage of video passthrough based solutions (Fraga-Lamas et al., 2018), while recent research suggests that the technology in question has matured to a capable level (Rajamäki et al., 2025). For all these reasons, a thorough review of the current research on XR applications in shipbuilding is called for—through a comprehensive understanding of this research, we can gain insights on the potential of XR within shipbuilding.

This paper presents a systematic literature review on the contemporary research on applications of XR technology within the shipbuilding industry. The review method employed is an independent dual review with adjunction; the reporting is conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method. The aim is to understand the state of contemporary research within the scope of the review, which is why we consider only articles published after the year 2015. The review takes into consideration the multiple subcategories and definitions for XR and the different phases of shipbuilding. The intended outcomes for this review are to evaluate the usage of different terms, like VR and AR, and identify how they are matched with different technologies (HMDs, mobile devices, desktop, wearables etc.), and to distinguish the phases and tasks within shipbuilding where they are employed. Also the value, success, and future directions of these deployments is examined and discussed. Concretely, the research questions addressed are as follows:

- RQ1: To what extent are XR technologies being researched and applied within the context of the shipbuilding industry?
- RQ2: How do different sub technologies of XR overlap with use cases within shipbuilding?
- RQ3: How is the value delivered by XR deployments in shipbuilding evaluated?

The remainder of the review is structured as follows: Section 2 defines the central terms used within the review; Section 3 presents the review methodology; Section 4 presents an overview of our findings in terms of thematic categories, gaps in the literature, and comparative analyses; and Section 5 discusses implications of the study's findings, strengths and weaknesses, and relates it to other systematic literature reviews. Finally, Section 6 presents the conclusions for this review.

This research is conducted as part of the Business Finland funded Virtual Sea Trial (VST) research project (UTU, 2024). The aim of the VST project is to research the virtualization of ship commissioning.

2 Terminology

To establish the scope of this review without ambiguity, we clarify what we mean by *XR* and by *shipbuilding*, as neither term has a standard crisply-defined meaning.

To define XR, the subcategories that make up XR must first be examined. The *reality-virtuality continuum* (Milgram and Kishino, 1994) is often regarded as the precursor for taxonomies describing immersive technologies. This continuum includes *augmented reality* (AR), virtual elements in an otherwise reality based scene, and *augmented virtuality* (AV), a virtual environment with real world details added. The AV term, though, has not gained popularity and solutions fitting the AV description are generally referred to with the other points of the reality-virtuality continuum. The extreme of the continuum is a fully virtual environment, which is simply referred to as VR. Milgram and Kishino also introduce the term *mixed reality* (MR) as an umbrella for the immersive technologies along the continuum, without including the ends of the continuum (excluding thus both VR and the real world).

The term extended reality was first used by Mann and Wyckoff in 1991, when discussing technologies that broaden human perception. Mann and Wyckoff argue that XR should be an extension of VR, where reality based sensing and interactions are included into a VR experience (Mann and Wyckoff, 1991). The use of XR as an umbrella term for immersive technologies is debated (Rauschnabel et al., 2022), and other terms, such as mixed reality by Milgram and Kishino, are sometimes preferred. In this review the term XR covers all the aforementioned immersive technologies. Of course when conducting searches for review material we included all the relevant terms, as detailed in Section 3.2.

Like XR, shipbuilding is not a strictly defined concept either. Shipbuilding as an industry is vast. Besides shipyards, it involves contractors and suppliers with ties to numerous fields (Kocak and Helvacioglu, 2021), from electronics (Raymarine, 2025), waste management (Wärtsilä, 2025), interior design to construction (PW, 2025) and more—shipbuilding is interconnected with numerous other fields of industry. In order to demarcate the topics within this review, we follow Kim et al., (2002) and take shipbuilding to include all the processes conducted by the shipyard responsible for the construction of a vessel. In particular, we exclude publications related to business functions, such as marketing and human resources, as well as those related to ship owner responsibilities, such as maintenance and operation.

3 Methodology

3.1 Systematic review protocol

Following the independent dual review with adjunction process, the study selection and screening, based on the same search results, was conducted independently by two researchers. Conflicting opinions regarding inclusion were resolved by a third reviewer. An independent dual review allows for the minimization of biases, while the inclusion of a third party for adjunction ensures that disagreements are solved in an impartial manner.

The *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) method was used for the reporting of this review. By following the PRISMA method we commit to a transparent and reproducible review that offers a complete view (Page et al., 2021) of the use of XR in shipbuilding.

3.2 Search strategy

The search databases utilized for this systematic literature review were the following: Association for Computer Machinery (ACM), EBSCO Host, Elsevier, Institute of Electrical Engineers (IEEE) Xplore, ProQuest, Scopus, Springer Computer Science, Springer Engineering, and Web Of Science (WOS). These databases were selected due to their stature as publication forums in the fields of software and computer technologies and technology research. ACM, IEEE Xplore and both Springer databases are vast collections of platforms for computer science and engineering related publications. Elsevier, Scopus, EBSCO Host and ProQuest and Web of Science are rich sources of multidisciplinary research. Combined, these databases cover a large variety of research topics relevant to technology and industrial applications.

In order to find all relevant literature that discusses the use of XR in shipbuilding on the selected publication forums, a broad range of search terms was used. One set of search terms was aimed at selecting the correct industry using variations of shipbuilding, another set directed the focus to industrial applications and commissioning, and finally, the last set concentrated the search on XR by including the multiple sub technologies and their abbreviations, and their synonyms. The complete search query is as follows:

`(("Ship building" OR "shipbuilding" OR "ship assembly") OR (("maritime" OR "naval" OR "marine") AND ("commissioning" OR "industry"))) AND ("mixed reality" OR "virtual reality" OR "extended reality" OR "augmented reality" OR "MR" OR "VR" OR "XR" OR "AR").`

Searches were conducted using keywords in titles and abstracts. The same search terms were applied across all databases whenever possible. However, site-specific limitations required some modifications. For example, abbreviations were excluded from searches in the Springer database because its keyword search includes full-text results, leading to irrelevant matches (e.g., "MR" interpreted as "mister" and "AR" as the verb "are"). Across all databases, these searches yielded a total of 2,436 results.

3.3 Inclusion and exclusion criteria

Articles that involved the shipping industry but were not strictly focusing on shipbuilding, such as articles on ship operation and maintenance, were excluded from this study. Similarly, articles not specifically focusing on XR technologies, such as wider technology reviews that mentioned XR only briefly, were excluded from this study. In order to focus on original sources, other literature reviews were excluded from the final results; they are discussed separately in Section 5.6. Finally, in order to maintain focus on contemporary and state of the art research, studies published before 2015 were excluded from this review—our window is thus roughly the past decade of research. The year 2015 also coincides with the announcement of the first widely available commercial VR and AR HMDs: both the Oculus Rift and the Microsoft HoloLens were announced in 2015, marking the beginning of the era of modern XR HMDs. Additionally, the widely popular HTC Vive (HTC, 2025) was announced in early 2016.

3.4 Study selection process

The process of study selection is visualized in Figure 1 using the use of a PRISMA flow diagram. The first numbers in the diagram correspond to the initial search conducted on 23.04.2024 and the latter ones to the supplementary search conducted on 30.5.2025.

Study selection began with the full 2436 studies retrieved from the databases. After the removal of duplicates, ineligible or redacted publications and unwanted formats (such as books, magazines and theses), a total of 1583 publications entered the screening phase. Screening began with an evaluation based on the titles and abstracts. 1376 records were considered out of scope and therefore excluded. Typical reasons for records being out of scope were that the record discussed only either shipbuilding or XR but not both, or that these topics were only examined as a part of a wider review of concepts, such as industry 4.0, not focusing specifically on XR or shipbuilding.

After the first round of screening, 207 articles were left for retrieval. 49 of these articles were not automatically available due to paywalls, and had to be re-evaluated based on the information available. Of the 49 unavailable articles, 17 were purchased and the rest were screened out based on the publication date, focus of the article or type of the document. The remaining 175 articles entered the final round of screening, where the full texts were evaluated for suitability. In the end, 44 papers were included in this review.

3.5 Limitations of the methodology

While we are confident that our search terms cover the essential literature, omissions are always possible. First, while the selection of databases used for this review is comparatively broad, it is not exhaustive: the inclusion of additional databases could have resulted in a larger initial set of records. Especially the inclusion of non-academic sources like trade magazines and other publications from sources not indexed in major databases may have provided interesting additions to the material of this review. An example of a trade magazine housing technology developments within the

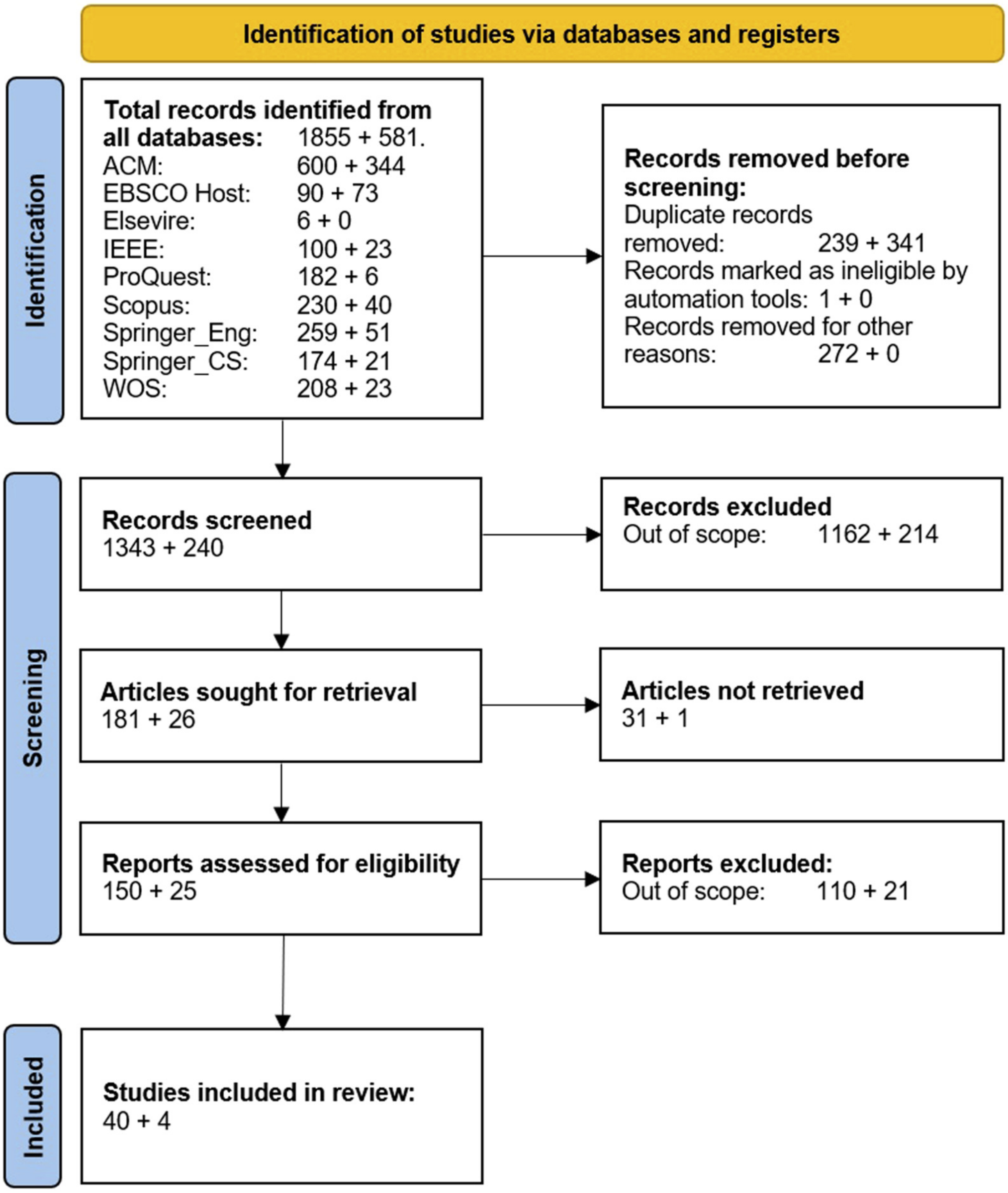

FIGURE 1
PRISMA Flow diagram denoting the identification, screening and final inclusion of publications.

shipbuilding sector is the *The Naval Architect* (RINA, 2026). The (COMPit, 2026) and (HIPER, 2015) conferences are examples of academic conferences not routinely indexed in major databases, but ones that may include topics relevant to this review. Second, we did not conduct exploratory searches comprising of open search methods enabled by modern artificial intelligence (AI). An AI based search might have yielded additional results. Third, we intentionally excluded the specific keyword "augmented virtuality" or "AV" from the search query. While AV was originally defined as a distinct category along the reality–virtuality continuum, the term itself has seen limited adoption in contemporary XR literature. Implementations that conceptually align with augmented virtuality are typically described using broader terms such as AV, VR, MR or XR. Consequently, we consider it unlikely that the exclusion of the specific AV keyword substantially affected the capture of relevant studies. However, it remains possible that isolated works explicitly employing only the term "AV" were not retrieved.

4 Findings

4.1 Overview of included studies

The 44 research papers we eventually selected to be reviewed describe work on both VR and AR technologies, and their applications to several phases of the shipbuilding process. A majority of the publications present some novel implementation designed to address a specific need within shipbuilding, and provide an evaluation of the implementation. Most commonly these

TABLE 1 Matrix of reviewed XR publications in shipbuilding.

Paper num.	Title/References	Year	Technology	Shipbuilding phase
1	3D CAD data extraction and conversion for application of AR/VR to the construction of ships and offshore structures (Han et al., 2019)	2019	Both	Multiple
2	A future foretaste: shipbuilding industrial tendencies (Fernandez and Cosma, 2020)	2020	Both	Multiple
3	A method to visualize the physical assembly sequence of ship intermediate products with augmented reality (AR) (Liu et al., 2021)	2021	AR	Manufacturing
4	A practical evaluation of commercial industrial AR systems in an industry 4.0 shipyard (Blanco-Novoa et al., 2018)	2018	AR	Inspection
5	A real-time physical progress measurement method for schedule performance control using vision, an AR marker and machine learning in a ship block assembly process (Choi and Seo, 2020)	2020	AR	Manufacturing
6	A review on industrial augmented reality systems for the industry 4.0 shipyard (Fraga-Lamas et al., 2018)	2018	AR	Multiple
7	A shared immersive virtual environment for improving ship design review (Jez et al., 2018)	2018	VR	Design
8	An innovative methodology for enabling predictive maintenance of ship systems based on industry 4.0 technologies (Bertagna et al., 2025)	2025	AR	Inspection
9	Analysis of the problems of using VR technology in shipbuilding design (Zakharov, 2023)	2023	VR	Design
10	Application of three - dimensional solid modeling of virtual reality technology in ship assembling (Wang, 2017)	2017	VR	Design
11	Application research of digital assembly system of marine turbocharger based on VR/AR (Chen et al., 2021)	2021	Both	Manufacturing
12	Applications & Advantages of employing digital ship design tools for newbuilding, retrofit and conversion projects (Borczyk and Singh, 2019)	2019	Both	Multiple
13	Augmented reality for an efficient inspection of outfitting process in shipbuilding (Miličević et al., 2021)	2021	AR	Inspection
14	Augmented reality for the visual inspection of pipes (Brisset et al., 2019)	2019	AR	Inspection
15	Comparative SWOT analysis of virtual reality and augmented reality ship passenger evacuation technologies (Vukelic et al., 2021)	2021	Both	Design
16	Creation of a virtual reality environment for teaching applied to a catamaran-type ferry, detailing the engine room (Garza Espinosa et al., 2023)	2023	VR	Design
17	Cross-platform AR annotation for assembly-design communication in pipe outfitting (Wang et al., 2022)	2022	AR	Manufacturing
18	Development of an AR based method for augmentation of 3D CAD data onto a real ship block image (Kim et al., 2018)	2018	AR	Manufacturing
19	Development of augmented reality system for productivity enhancement in offshore plant construction (Choi and Park, 2021)	2021	AR	Manufacturing
20	Development of augmented reality technology implementation in a shipbuilding project realization process (Kunkera et al., 2024)	2024	AR	Manufacturing
21	Digital transformation, applications, and vulnerabilities in maritime and shipbuilding ecosystems (Diaz et al., 2023)	2022	AR	Design
22	Digital mock-up and working simulation on Mixed Reality (Nagano, 2015)	2015	AR	Design
23	Efficient 3D design drawing visualization based on mobile augmented reality (Oh et al., 2015)	2015	AR	Design
24	Forming a view: a human factors case study of augmented reality collaboration in assembly (O'Keeffe et al., 2024)	2024	AR	Design
25	How virtual reality is used in industrial maritime design processes: Two case studies (Gernez et al., 2023)	2023	VR	Design
26	Initial lessons from application of virtual reality to warship design (Bradbeer, 2016)	2016	VR	Design
27	Integrating virtual reality software into the early stages of ship design (Cassar et al., 2019)	2019	VR	Design

(*Continued*)

TABLE 1 Continued

Paper num.	Title/References	Year	Technology	Shipbuilding phase
28	MAGIC: multi-user advanced graphic immersive configurator for sustainable customization of complex design products—a sailing yacht case study (Piccininni et al., 2025)	2025	VR	Design
29	Methodology and challenges of implementing advanced technological solutions in small and medium shipyards: the case study of the Mari4_YARD project (Grazi et al., 2025)	2025	Both	Multiple
30	Minimising the designer/ end user knowledge gap using virtual reality (Pynn, 2017)	2017	VR	Design
31	Mixed reality for industry? An empirical user experience study (Heimo et al., 2020)	2020	Both	Multiple
32	Monitoring maritime industry 4.0 systems through VR environments (Tsigkounis et al., 2021)	2021	VR	Manufacturing
33	Position-based augmented reality platform for aiding construction and inspection of offshore plants (Choi et al., 2020)	2020	AR	Inspection
34	Prediction of graphic interaction time of virtual reality system based on improved Fitts' Law. (Zhenghong et al., 2020)	2020	VR	Design
35	Project management for cooperative development of welding safety training system using virtual reality (Li et al., 2023)	2023	VR	Manufacturing
36	Reducing shipbuilding touch labor costs with AR (Rando et al., 2015)	2015	AR	Manufacturing
37	Registration method for maintenance-work support based on augmented-reality-model generation from drawing data (Lee et al., 2020)	2020	AR	Inspection
38	Use of wearable and augmented reality technologies in industrial maintenance work (Aromaa et al., 2016)	2016	AR	Inspection
39	Using virtual reality paradigm to present ship structures in cad environment Šikić (2017)	2017	VR	Design
40	Virtual reality in a shipbuilding environment (Perez Fernandez and Alonso, 2015)	2015	VR	Multiple
41	Virtual reality in shipbuilding: Three use cases in a cruise ship design process (Schiavon et al., 2019)	2019	VR	Design
42	Virtual reality: tool or toy for shipbuilding? (Martin, 2019)	2019	VR	Design
43	Visual inspection with augmented reality head-mounted display: an Australian usability case study (Howard et al., 2023)	2023	AR	Inspection
44	Cognitive load evaluation of outfitting AR visual information (Wang et al., 2024)	2024	AR	Inspection

FIGURE 2
Articles by year and technology.

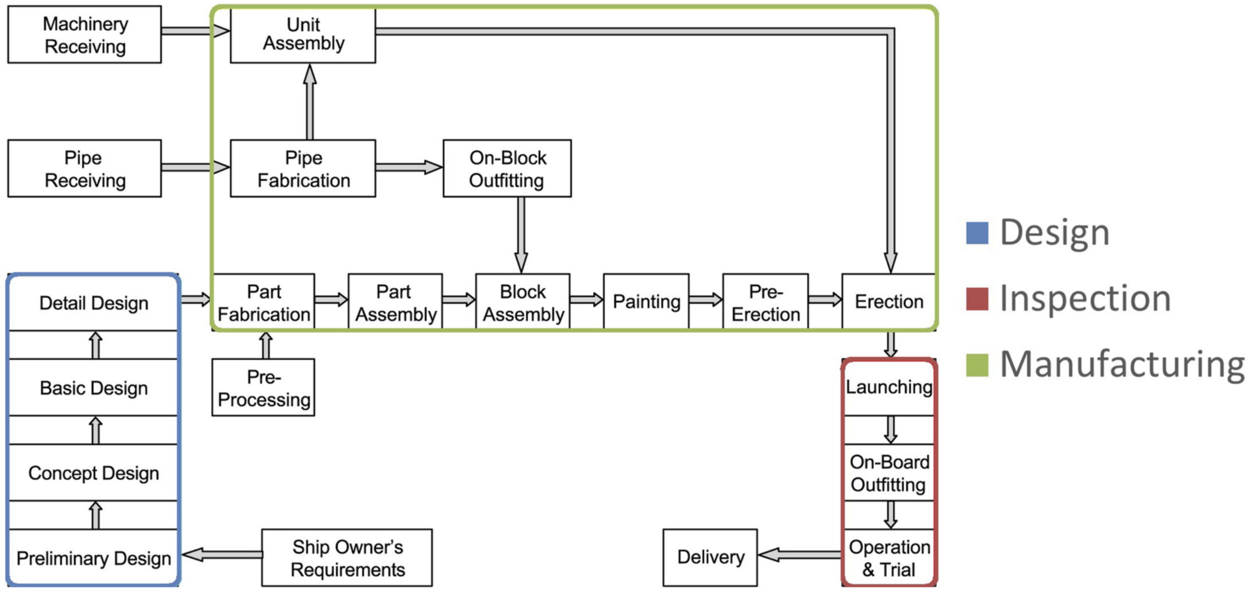

FIGURE 3
Shipbuilding phases (from Kim et al., 2002).

evaluations were conducted by obtaining user feedback or by site testing. Publication forums for the selected papers were journals in computer science, engineering and maritime; the Royal Institute of Naval Architects (RINA) journal (RINA, 2025) stands out with altogether nine publications. Table 1 shows the list of the selected articles, including the publication year, XR technology used, and shipbuilding phase. In terms of technologies discussed, the 44 publications displayed a consistent rate of research over the past 10 years. 17 publications discussed exclusively VR technologies, 21 discussed AR technologies and the remaining 6 addressed both types of XR to some extent. Publications over time are visualized in Figure 2.

To form a precise picture of how XR technologies are applied in shipbuilding, it is useful to distinguish between different phases of the shipbuilding process and classify the publications under review using these phases as one criterion. Derived from an outline provided by Kim et al. (2002) (visualized in Figure 3), we can identify three coarse phases that represent clearly differing requirements in terms of technology and usability:

- Design
- Manufacturing
- Inspection

The design phase is focused on the initial phases of shipbuilding, during which preliminary concepts are developed based on the ship owner's requirements. The design phase is considered to continue until the fabrication of parts begins. In the publications selected for this review, the design phase is characterized by a focus on 3D computer assisted design (CAD) models, design reviews and collaboration between stakeholders.

The manufacturing phase that starts with parts fabrication is extensive and consists of numerous assembly, painting and outfitting tasks. Manufacturing is the broadest of the three distinct categories, and also represents the widest array of solutions in the reviewed publications. Proposed XR solutions for manufacturing range from information and guidance tools aimed for assisting with installations to training solutions for improving safety.

The inspection phase is not originally outlined by Kim et al. as a distinct phase of shipbuilding. Due to its extensive representation within the reviewed articles, however, we consider it to be a standalone phase. The inspection phase refers to the final phase of the shipbuilding process, during which different trials and tests are performed. The publications targeting the inspection phase display a focus on information accessing and reporting tools. Following the outline of Kim et al., the inspection phase includes the tasks following the launching of the ship.

Most (17) of the selected research papers focused on applications for the design phase, with somewhat fewer articles discussing the manufacturing (11) and inspection (9) phases. Seven of the publications were reviews that took a broader perspective and were considered to focus on multiple application categories. Figure 4 charts the number of articles published on each of the shipbuilding phases by year.

4.2 Technology vs. shipbuilding phase

The reviewed articles reveal a pattern in the usage of different technologies during different phases of shipbuilding. Virtual reality is heavily preferred during the design phase; of the strictly VR focused articles, 13 (81.25%) discussed design and only 2 (12.5%) papers addressed manufacturing. One VR paper (6.25%) focused on multiple phases of shipbuilding.

Augmented reality, on the other hand, is present mostly in the manufacturing and inspection phases: 8 (36%) of the AR papers focused on manufacturing and 9 (41%) on inspection, which totals

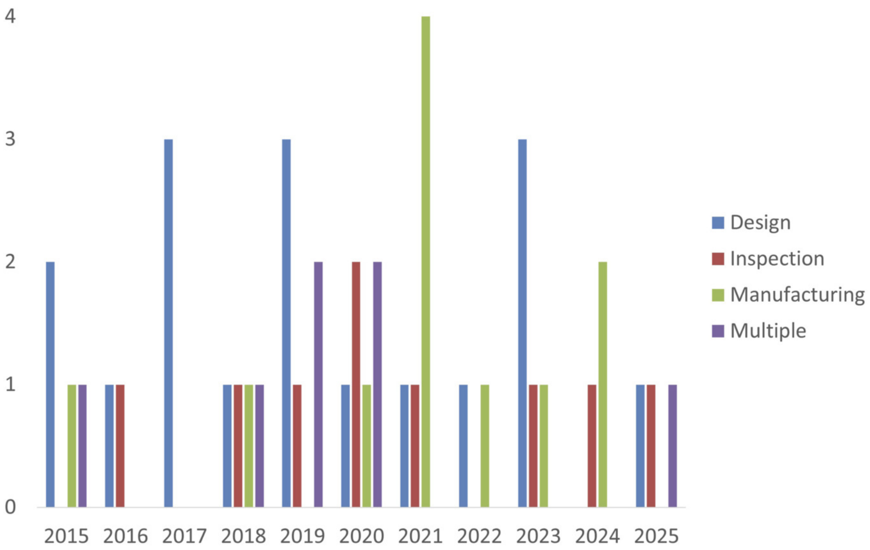

FIGURE 4
Articles by year and shipbuilding phase.

TABLE 2 XR Technology vs. shipbuilding phase.

Shipbuilding phase	VR	AR	Both
Design	13	3	1
Manufacturing	2	8	1
Inspection	0	9	0
Multiple	1	1	5

77% of all AR papers. Of the remaining 33% of the AR papers, 3 (14%) focus on design and one (9%) focuses on multiple phases.

Most papers that discussed both VR and AR focused on multiple phases of shipbuilding: 5 (71%) addressed multiple phases, one focused on manufacturing and one discussed the design phase. Table 2 shows the cross-tabulation of the shipbuilding phases and XR technologies.

Different XR technologies include a variety of implementations. Design related VR studies predominantly examined immersive environments for CAD model visualization (p7, p10, p34, p39, p42) and design reviews (p9, p16, p25, p26, p27, p28, p30, p41), while the few manufacturing focused VR works explored virtual assembly planning (p32) and welding safety (p35).

Like the articles showcasing VR solutions, the articles featuring AR solutions also have distinct use cases within the shipbuilding process. AR studies in manufacturing were largely marker based AR systems designed to support assembly tasks (p3, p5, p17, p18, p19, p20, p24, p36), whereas inspection focused AR publications discussed the use of AR systems for visual overlays during pipe and outfitting quality checks (p4, p8, p13, p14, p33, p37, p38, p43, p44).

A general pattern can be observed: VR papers tend to focus on design, whereas AR papers primarily address manufacturing and inspection. However, there are some outliers. Rather than focus on a specific use case for AR, Fraga-Lamas et al. adopt a holistic approach to the usage of AR within shipbuilding, while presenting examples from a variety of platforms and applications (p6). Design focused AR papers use familiar methods, such as model overlays and marker based tracking, but present them in novel use cases: Diaz et al. apply AR in digital prototyping, for which other papers present VR solutions. Employing a similar 3D CAD model as other authors have inspected in VR, Diaz et al. use an AR HMD to overlay the model within the real confines of a ship under construction (p4). This approach blurs the lines between the design and manufacturing phases, and presents a paradigm only enabled by XR technologies. In a similar vein, Nagano in their 2015 paper discusses the use of early video passthrough technology to review designs in confined spaces (p22). The AR design paper by Oh et al. presents an image recognition based mobile AR solution for visualizing 3D structures from 2D designs (p23).

The publications focusing on both VR an AR technologies were primarily reviews of the use of XR within shipbuilding. Unlike the papers specific to either VR or AR, these reviews often spanned the entirety of the shipbuilding process and presented overall reviews (p2, p12, p29, p31). Some authors do, however, take a more narrow focus: Han et al. present a pipeline for the conversion of 3D CAD to XR compatible formats, while using shipbuilding as a case study (p1). The paper on HMD implementation by Chen et al., which was outlined in the introduction, is another example of a paper that describes the use of multiple XR technologies, but this time focusing on the manufacturing phase. Chen et al. present both a VR and an AR solution for the digital assembly system of a marine turbocharger (p11). A SWOT analysis of VR/AR technologies for evacuation simulations presented by Vukelic et al. serves as an example of a paper applying multiple XR technologies and focusing on the design phase. Vukelic et al. compare and contrast the values of both VR and AR technologies for simulations and reflect on their value during ship design (p15).

TABLE 3 Types of XR platforms.

Type of XR platform	AR	VR
Mobile Device	12	0
HMD	9	14
Other	2	2

4.3 Types of extended reality platforms and solutions

To better understand how XR was implemented in practice, this section examines the platforms used in the pilot implementations reported across the reviewed studies. The XR platforms used in pilot implementations designed within in the reviewed articles are presented in Table 3. Of the 21 papers focusing on AR and seven papers detailing both XR technologies, 23 papers presented AR pilot implementations, which were developed and evaluated as part of the publication. Of these AR pilot implementations, 12 were mobile device (tablet/phone) AR solutions for design information or model visualization (p4, p8, p13, p14, p17, p18, p19, p20, p23, p29, p33, p37). The remaining 11 papers included nine HMD implementations, of which seven were based on the HoloLens line of HMD (p11, p17, p21, p24, p31, p43, p44), two on other HMD devices (p22, p38), and two featured external static cameras (p5, p36).

The VR solutions varied more in the types of platforms presented. Of the 16 papers discussing exclusively VR and seven papers discussing both VR and AR, 16 papers presented a VR pilot implementation. Of these papers, 14 presented HMD based VR pilot implementations. The most popular HMD for research purposes was the HTC VIVE, five publications used VIVE VR for various tasks in design (p11, p27, p30, p31, p34) and one for welding safety training (p35). Other popular HMD platforms were the Oculus Rift (in earlier papers) (p7, p26, p30) and later its successors the Quest series (p16, p25, p28). The remaining two papers describing HMD implementations featured a mobile device VR setup by Tsigkounis et al. (p32) and a non-specified VR setup focusing on 3D model transformations by Schiavon et al. (p41). The final two VR papers presented non-HMD implementations: Wang presents a desktop 3D simulation of ship assembly (p10) and Grazi et al. evaluate a CAVE VR system as part of their review of different XR systems for the shipbuilding industry (p29).

4.4 Research methodologies

Beyond examining the types of XR technologies applied and described in the selected publications, it is also relevant to consider how these technologies were researched and evaluated. Most of the selected publications reported pilot studies. Of the 44 articles reviewed in this study, 33 presented a pilot implementation addressing a specific need. These pilot implementations can be categorized into three groups:

- Studies that did not perform any user testing (15 of 33 papers).
- Studies that performed evaluation via test user feedback (10 of 33 papers).
- Studies that conducted performance metrics based evaluations (8 of 33).

Studies which did not perform any user testing generally rather presented a proof of concept and verified that the proof of concept functions as expected. Often these studies present a novel concept or application, which upon further research, could be developed into an industrial application for the shipbuilding sector. (p4, p7, p10, p13, p16, p18, p20, p21, p23, p26, p27, p33, p36, p39, p40).

Evaluations based on test user feedback used a variety of metrics, of which the SUS and NASA-TLX were the most frequently used. Often multiple instruments were used in conjunction, as they capture distinct dimensions of subjective user-reported performance (e.g., usability, workload, acceptance). Bertagna et al. deliver an XR inspection and predictive maintenance tool and evaluated it with ship design and operation personnel (p8). Wang et al. evaluated their cross platform tool for assembly-design communication with the use of test users simulating a work scenario. The evaluation included a SUS questionnaire as well as custom task difficulty, efficiency and help information questions (p17). Nagano tested their early MR system with a simulated trial with test users (p22). O'Keeffe et al. in their research present a testing session for AR support during assembly tasks. Results of the testing are evaluated using the SUS and NASA-TLX metrics (p24). Piccininni et al. performed testing using convenience sampling in a laboratory setting and evaluated the usability of their VR system using both the SUS and a custom questionnaire evaluating: the implemented features, level of immersion, graphical rendering quality, emotional impact, and improvement suggestions (p28). In their research into the use of VR systems to reduce designer-end user gap, Pynn et al. present findings gathered via a questionnaire presented to shipbuilding professionals (p30). Heimo et al. in their research present a multitude of XR solutions tested with industry partners and evaluated via the use of multiple choice questionnaires presented to test users and observations made by test conductors (p31). Aromaa et al. evaluated the use of wearable and AR technologies in an industrial setting and gathered feedback from test users via SUS and technology acceptance model (TAM) questionnaires, as well as interviews (p38). In their research pertaining to the visualization of CAD models in 3D environments, Schiavon et al. gathered feedback from test users associated with design processes (p41). Howard et al. in their research into the deployment of AR HMDs for inspection tasks within the Australian shipbuilding industry use the SUS and NASA-TLX metrics, as well as, custom usefulness and physical aspects questionnaire questions for evaluation (p43).

Compared to test user feedback evaluation, performance metrics testing showed more variety in methodology, but generally evaluated performance of the pilot implementations by tracking time or accuracy of completed tasks. These quantitative means were most often used to evaluate manufacturing and inspection associated pilot implementations: Choi and Seo evaluated their AR manufacturing progress measurement tool by comparing two assembly teams in an on-site setting (p5). Chen et al. measured the efficiency of using XR tools during a marine turbocharger assembly process using a novel method developed as part of their research (p11). Brisset et al. measured inspection rates of pipes and include a return of investment (ROI) analysis as part of their research into inspection related AR (p14). In their paper about AR-assisted manufacturing verification, Choi and Park measured the execution times of different verification tasks and report increased efficiency when workers utilize their AR tool (p19). In their review of industrial applications of advanced technical solutions, Grazi et al. present time and work savings, as well as a ROI analysis of multiple different AR systems (p29). Tsigkounis et al. tested the viability of using a VR system to monitor industrial control rooms in a maritime environment and evaluated the response times of participants (p32). Li et al. report external enterprise evaluation for the efficacy of the authors' VR welding safety management tool (p35). Gernez et al. deploy a VR system in support of the design process and present findings based on the amount of realized use of the deployment during a real design process (p25).

Some publications even make presenting novel evaluation methods for measuring the success of XR solutions a primary focus: Chen et al. in their evaluation of the efficacy of AR/VR tools for assembly heavily focus on analyzing the efficiency of the manufacturing of marine turbochargers using AR/VR tools (p11). Zhenghong et al. in their research present a novel evaluation method for VR interaction times, while using the shipbuilding industry as a case study (p34). Wang et al. argue that contemporary means of cognitive load evaluation (including NASA-TLX) are not sufficient, and present an improved method for evaluating cognitive load of workers performing outfitting tasks with the help of AR tools (p44).

4.5 Comparative analysis

Differing use of terms is an important consideration when reviewing research. The papers we examined are mostly in agreement about terminology, but there are some outliers. Certain terms are used relatively rarely. Mixed reality is an example of a term that saw quite marginal use. As discussed in Section 2, Milgram's and Kishino's definition of mixed reality refers to an umbrella of immersive technologies, which does not include VR. Since augmented virtuality has effectively fully fallen out of popularity, only the augmented reality portion of mixed reality sees use. Despite this, a few authors do use MR in their works: Fernandez and Cosma in their future forecast of industrial tendencies for the shipbuilding industry refer to mixed reality as a merging of VR and AR, but do not give concrete examples (p2). Nagano uses the term for their digital mock up system using an early video passthrough HMD, much in accordance with the Milgram & Kishino definition (p22). Grazi et al., in their review of advanced technological solutions, make a distinction between mixed and augmented realities, which does not conform to Milgram's and Kishino's definition: "AR fully immerses operators in a virtual world for training and knowledge improvement. Meanwhile, MR merges the real and virtual worlds, providing virtual data and information where and when needed". The authors do not further use the term MR in their work, however, and use AR to describe (among other deployments) typical 3D overlay tools like many of the other authors (p29). Heimo et al. use the term mixed reality, when evaluating immersive technologies within the shipbuilding industry, while (even in the authors' own nomenclatures) describing either AR or VR solutions (p31). Besides the aforementioned examples, others papers discussing both technologies referred directly to AR and VR without the use of an umbrella term (p1, p2, p11, p12, p15, p29, p1). The term extended reality saw no use.

Beyond MR, other differing uses of terminology are present: VR is consistently used to describe HMD setups or CAVE VR setups, with the exception of Wang in their research describing a desktop simulation (p10). As detailed in previous sections, AR papers mostly detail hand-held mobile systems or AR HMDs but a few exception exist: (1) as mentioned in the introduction, Choi and Seo use the term augmented reality to refer to markers recognized by external cameras (p5); (2) as mentioned in the previous paragraph, Grazi et al. have a distinct definition for AR systems and use AR to describe a variety of implementations ranging from CAVE VR style projections to XR HMDs (p29); and (3) Rando et al., in their 2015 paper research the use AR in reducing redundant labor during shipbuilding, define AR through its tracking and highlighting capabilities and outline an external XBOX Kinect based tracking system. This is somewhat of a departure of the otherwise self contained solutions other authors present (p36).

A deeper examination of technical details of the pilot implementations reveals further commonalities besides just the choice of the XR platform. Many of the authors focus on similar requirements, such as robust tracking and efficient access to data, and use similar technical solutions to address these requirements. Papers focusing on AR implicitly, through their implementations, denote the importance of robust tracking: multiple of papers focusing on AR specifically detail a marker based tracking system (p4, p5, p8, p13, p17, p19, p20, p37). Some authors, however, take a markerless approach (p14, p18, p31, p36). Just as for the papers focusing on AR, we can recognize central themes for the implementations in the papers focusing on VR. The capacity to use existing 3D CAD models as the starting point for VR solutions and focus on methods for converting CAD models to VR compatible formats is present in multiple publications (p1, p7, p39, p40, p41).

As we have established above, several of the examined papers present pilot implementations, and also some kind of a verification or evaluation of that implementation. Some papers report results of user testing, and in general, across the material reviewed, usability measurements (like the system usability scale and tester feedback) show that the XR implementations are met with enthusiasm and have reached an acceptable to high level of usability. Despite these promising findings, the authors describing the pilot implementations recognize that the technology is still at an early state, and needs further development to reach maturity, and that increased training by end users on the use of XR tools is required to reach the full capabilities of the technology (p4, p6, p7, p8, p9, p15, p16, p18, p22, p24, p26, p28, p31, p33, p36, p39, p43).

A final set of findings focuses on the results of the technology reviews that we included in our set of papers to examine. In their 2020 future forecast of emergent technologies for the future of shipbuilding, Fernandez and Cosma outline the potential of AR/VR (p2). Fragas-Lamas et al., in 2018 conducted a review of industrial AR systems for shipbuilding. In their review, the authors recognize the potential of the technology, but note that the hardware capabilities are not yet at a sufficient level (p6). In 2019 Borczyk and Singh conducted research regarding the use of XR technologies in shipbuilding. The authors recognized the potential of XR and note that it is important to accept these technologies as future mainstays in the industry (p12). In their 2025 review of implementing advanced technologies in shipyards, Grazi et al. recognized the value of a set of specific AR deployments in multiple areas of the shipbuilding industry and were able to demonstrate this value through a quantitative evaluation (p29). Heimo et al. denote in their 2020 review that end users are enthusiastic and willing to accept the introduction of XR systems into their work, but also emphasize that deployment targets must be decided carefully (p31). In an early study of the potential of VR systems in shipbuilding, Pérez Fernández and Alonso (2015) recognize the potential of VR systems in multiple phases of shipbuilding, and highlight especially their compatibility with existing 3D formats used in shipbuilding (p40).

5 Discussion

5.1 State of XR technology research within shipbuilding

Reflecting on the first research question (RQ1), two factors are particularly relevant: the volume of published research and the maturity of the reported implementations. Over the past decade, both AR and VR applications in shipbuilding have been actively investigated. The distribution of publications over time does not reveal a clear upward or downward trend (see Figure 2), suggesting relatively stable research interest in both technologies. The maturity of implementations can be interpreted using Technology Readiness Levels (TRLs) (Mankins, 1995), which range from TRL 1 (basic principles observed) to TRL 9 (full-scale operational deployment). While this review does not perform a formal TRL assessment, the framework provides a useful lens for characterizing the state of research. TRL 3 corresponds to proof of concept validation of critical functionality, TRL four to laboratory testing, and TRL 5 to validation in relevant operational environments.

Nearly three quarters of the studies reviewed in this paper center on developing pilot implementations, often emphasizing technical feasibility rather than systematic end-user evaluation or quantitative performance assessment. Approximately half of the reviewed articles—which present proof of concept implementations—offer no formal evaluation. These studies are broadly comparable to TRL 3. A further quarter report validation relying on subjective user feedback, while only about a quarter describe on-site testing in operational environments. Different evaluation categories are presented in Section 4.4. User studies, when conducted, typically focus on usability and acceptance, representing a stage of validation broadly comparable to TRL 4. Only a minority of studies report performance metrics based on-site testing comparable to TRL 5. The distribution of studies across evaluation types suggests that most XR implementations in shipbuilding remain at TRL 3–4. The available evidence suggests that the integration of XR technologies into shipbuilding workflows has not yet reached a mature and widespread operational state. Although the underlying XR technologies are themselves mature, their integration into shipbuilding workflows appears to be progressing gradually toward operational deployment.

An additional way to analyze the overall state of the XR research in the shipbuilding industry is by examining the findings of the technology review articles included in the material of this systematic literature review. While these reviews focus on individual aspects and deployments of XR technologies, the progress from 2015 to 2025 shows an advancement from forecasts and recognitions of potential to realization of specific value. The earliest included reviews of VR and AR in shipbuilding (p40, 2015 & p6, 2018) recognize the potential of the technologies, but conclude that the technology needs to mature further before deployments can be made. Later reviews (p2, 2020 & p31, 2020) assert that clear acceptance and value can be delivered if correct use cases can be identified, and that a majority of companies using XR solutions are at an experimental phase. Finally, the latest review (p29, 2025) denotes that quantitative value is delivered by tested deployments, and that XR solutions have direct use cases in supporting multiple documentation and data retrieval related tasks. Although the number of reviews is small, they do indicate a shift from mere experiments to deployments into practice. This signal is still weak, XR technologies in shipbuilding have not reached a mature state and examples of successful deployments are few.

5.2 Technology types and implementation targets

Research question two (RQ2) examines the types of XR solutions and where they are deployed. Section 4.2 presents clear patterns in applying different XR technologies in different phases of the shipbuilding process. VR solutions are favored in the design phase and AR solutions are more present during the manufacturing and inspection phases. The reason why technologies are dispersed between the different phases in this manner is quite evident based on the different use cases reported in the analyzed papers. VR allows for prototypes and digital models to be "brought to life" early before they have been constructed. This allows for tasks such as visualizing design models in an intuitive 3D space and performing design reviews on virtual prototypes. AR solutions, on the other hand, enable tasks that require workers to interact with real world items and systems. AR deployments featured capabilities such as marker based tracking for recognizing individual components or areas within ships, allowing for tasks like quality checks and validations.

While the application of the two XR technologies to different tasks is generally clear, the choices for XR platforms are at times somewhat surprising. VR appears to be a relatively mature technology, with research deployments following market leading HMDs over time, evolving from early systems such as the Oculus Rift to the HTC Vive and, more recently, the Quest series. In contrast, AR technologies show far less development. Mobile device based AR solutions relying on marker based navigation are still being investigated in papers published as recently as 2024 (p20). Although some AR studies employ HMDs, the majority of publications focus on mobile devices, and among these, marker based tracking dominates. Marker based mobile AR systems were already shown to be functional in the earliest industrial AR reviews (p4). Nevertheless, this approach continues to occupy a prominent place in current research, despite review findings indicating that such systems are not widely deployed in real world settings. The continued preference for marker based tracking may be attributed to its robustness and to the familiarity and accessibility of mobile devices for end users. Even so, AR implementations in shipbuilding have yet to demonstrate large scale or sustained deployments.

5.3 Evaluation and value delivery of XR solutions

The final research question (RQ3) focuses on how XR solutions within the shipbuilding industry are evaluated. As detailed in Section 4.4, we identified three main categories of evaluations in the articles examined in this review. These three categories reflect increasing levels of methodological rigor and technological maturity, from functional feasibility verification to subjective user validation and finally to objective operational performance measurement.

Proof of concept evaluations, which do not perform user testing, are used to verify the functionality of novel pilot implementations. They represent the most common type of evaluation in research on XR solutions for shipbuilding. These evaluations do not include end user testing or quantitative performance metrics testing. The heavy reliance on proof of concept studies indicates that the field is still in an early stage of development.

User feedback and performance metrics based evaluations are tied closely as the next most common methods for assessing pilot implementations. User feedback provides insight into technology acceptance, usability, and user attitudes. While user feedback is typically subjective at the individual level, aggregated results across groups can yield quantitative findings. Performance metrics based evaluations offer the most unambiguous means of measuring the value delivered by these solutions. About a quarter of reviewed studies reported performance metrics from on-site trials, and these results were generally promising. Notably, studies employing performance metrics tend to represent more recent research, with most published between 2020 and 2023, corresponding to the latter half of the papers included in this review.

The results shown by the evaluations of XR implementations support the findings of the technology reviews presented earlier. XR solutions can be deployed in real use cases and value can be gained from these deployments. Crucial considerations have to be made regarding the deployment targets. Performance metric evaluations chronologically falling towards the latter half of articles also shows support for the gradual advancement of the field of research. Increasing amounts of research is being evaluated and applied on site and in practice. Despite the advancements, however, the applied solutions are still often niche.

5.4 Gaps in the literature

As alluded to in Sections 4.4, 5.1, 5.3, the reviewed articles focus heavily on pilot studies and do not present robust evaluations. The results of these studies show promise in terms of capabilities of the XR technologies, as well as potential identification of use cases during the shipbuilding process. Despite this promise, wide-scale deployments are not represented in the literature. Quantitative studies evaluating the capabilities of the pilot implementations are rare, with the few publications discussed above in Section 4.4 being the sole exceptions. Finally, since research is focused heavily on pilot implementations, very few integrations into existing ecosystems or life cycle reviews delivering return of investment analyses for XR applications are presented. It should be noted, however, that the return of investment analyses in general for any novel technology are rare and require close collaboration between the industry and research institutions for prolonged periods of time.

In addition to reflecting the early stage of research, the technology choices described in the literature also reveal a lack of diversity in hardware. One notable omission is the use of video passthrough based AR functionality. Video passthrough AR uses front-facing cameras, which are standard in modern HMDs, to display the user's real-world surroundings. A likely explanation for the absence of passthrough based solutions is the relative novelty of the technology. Recent HMDs from major manufacturers—such as the Meta Quest 3 (released October 2023) (Meta, 2025) and Apple Vision Pro (released February 2024) (Apple, 2025)—support passthrough capabilities, but research conducted on these platforms within the shipbuilding setting is likely still in progress. Passthrough based AR could offer a wider field of view and richer interaction opportunities than optical see-through devices such as the HoloLens, while still retaining the benefits of head-mounted displays, in contrast to mobile AR solutions.

5.5 Future directions

Based on the reviewed literature, some recommendations and forecasts for the future of XR technologies in shipbuilding can be made. The number of pilot implementations using similar technologies and identifying similar use cases suggests that early phases of research are being concluded, and that the next phase of research should be the wide-scale deployment of these identified technologies within the identified use cases. Research should focus on potential ways in which the previously presented pilots can be evaluated in real world use and how they can be leveraged to improve existing workflows within shipbuilding.

The core consideration when seeking to deploy pilot implementations is the integration into existing systems and workflows. Many of the articles reviewed recognize the innate synergy between 3D design models and XR technologies, but in order to successfully deploy novel technologies, they must also fit into existing information systems and the daily workflows of end users.

While many technologies—such as mobile device AR and the use of VR head-mounted displays in design—are well established in the research literature, more recent hardware paradigms remain largely unexplored in shipbuilding contexts. Recent advances in processing power have led industry leaders, including Apple and Meta, to shift toward video passthrough systems in their devices. Although these systems are commercially available and technologically mature, none of the reviewed studies reported their application in shipbuilding environments. This absence suggests a potential gap between advancements in XR hardware and their evaluation in the shipbuilding settings. Future research could therefore investigate the feasibility of passthrough based systems in shipbuilding workflows.

A technology that has massively impacted the digital landscape is artificial intelligence. Future research and development into XR should also consider how AI best fits into XR solutions. Image recognition capable HMDs that use AI to comprehend the scene in their field of view could overcome the need for predetermined feature tracking and use of markers. Similarly, AI can assist in converting digital models to XR compatible formats, which is a core requirement for using design models in XR solutions. Additionally, the introduction of personalized AI agents can be enabled by XR solutions: XR can be leveraged to allow for new forms of human machine interaction between AI agents and human users.

5.6 Comparisons to other systematic literature reviews

Other systematic reviews focusing on the use of XR technologies within shipbuilding were not found at the time of conducting this review. Reviews with different focuses and from different industries, however, have been published: van den Oever et al. performed a systematic literature review on the use of AR in maritime collaboration in 2022 (van den Oever et al., 2024). Pedram and Piatkowski published a systematic literature review regarding the use of VR in mental healthcare in 2025 (Pedram and Piatkowski, 2025), and Stracke et al. published a 2025 systematic literature review regarding VR in education (Stracke et al., 2025). This is by no means and exhaustive list, there are likely other reviews about the use of XR in industry, but the three reviews selected present uses of different XR technologies across distinct application domains, thereby providing useful points of comparison.

Van den Oeven et al. research maritime collaboration instead of shipbuilding, but the results show similarities with the findings of this review. In types of technology, although only one article is shared between their review and ours. Their search query matched 781 articles from the IEEE Xplore and WOS databases. After duplicate removal, 691 articles remained for screening. Following full-text assessment, the authors ultimately included 32 studies published between 2010 and 2022. In their conclusion the authors note similar findings as this review: there is *“thriving literature on AR prototypes”* (van den Oever et al., 2024), but it would be beneficial to try to develop prototypes to higher technology readiness levels rather than continuously developing new prototypes and proofs of concept, which overlap with existing research.

In their review of the use of VR in mental healthcare, Pedram and Piatkowski received 534 hits from the PubMed, IEEE Xplore, Science Direct, Scopus and WOS databases, and screen 424 articles with 65 articles ultimately included in the review. The healthcare industry differs in needs and requirements vastly, when compared to the shipbuilding industry, and the review by Pedram and Piatkowski focuses entirely on VR, while this review focuses on the entirety of XR technologies. Similarities in the findings of the two reviews can, however, be found. Pedram and Piatkowski note the potential of immersive technologies in the healthcare industry, but note that research should move towards integrating immersive technologies into existing practices. This finding is very much in line with the findings of this review.

Stracke et al. in their review of VR technologies for higher education screen 291 articles and include a list of 50 publications into their final review. The scope of the review (focusing solely on VR, rather than all of XR) and target industry differ to this review, but similarities can be found in the findings. Quoting Stracke et al. *“Notably, the majority of the 50 articles do not present evidence based and validated results”* (Stracke et al., 2025). This observation aligns with findings in the present review, where many studies remain exploratory in nature and represent low to intermediate levels of technology readiness. Still, however, in the educational industry (as with shipbuilding) potential use cases have been successfully identified.

6 Conclusion

This systematic literature review sets out to examine the state of the art research into the use of extended reality within shipbuilding over the past decade. To our knowledge, this is the first study examining the use of XR in shipbuilding in a holistic and systematic way. A total of 44 peer reviewed articles gathered from nine central databases were reviewed. The identification of these studies was conducted in strict adherence to the PRISMA protocol.

We categorized the reviewed research between the two most frequently used sub-technologies of XR: augmented reality and virtual reality. Our findings show that both technologies have seen steady research over the time frame of the review, and that most of the research is at an early state and focuses heavily on pilot implementations of proofs of concepts. This notion of early state of research is reinforced by the way the research implementations are evaluated: about half of the research articles do not describe end user or on-site evaluations of the proposed implementations. An emphasis on the early state of research is also visible in the technology review articles we examined as part of this systematic review.

Our review clearly shows that different sub-technologies of XR see different use cases on different phases of shipbuilding. VR technologies are primarily used in the design phase, during which physical constructs have yet to be assembled and digital mediums are used. Common use cases are design reviews, model visualization and participatory design. VR implementations were heavily focused on the use of head mounted displays. AR technologies on the other hand were focused on the assembly and inspection phases of shipbuilding. Common use cases are overlaying design information with real world counterparts and validating assembly products via comparison with design models. AR solutions saw slightly more mobile device based implementations than head mounted display implementations.

Pilot implementations were evaluated in one of three ways: proof of concept validation, user feedback testing or performance metrics testing. Half of the pilot implementations were evaluated as a proof of concept, and no systematic evaluation was conducted. One fourth was evaluated based on user feedback of laboratory and limited deployment testing. The results of such tests generally indicate that XR deployments reach an acceptable level of usability and that users show enthusiasm towards applying XR technologies in their domains. The remaining fourth of the research papers base their evaluations on a multitude of different performance metrics that were aimed at assessing the potential of XR technology in a real world setting. These deployments that were tested in real world settings showed demonstrable value in increasing the efficiency of the performed tasks. Overall, despite the amount of actual real world deployments being low, the results show that with correctly identified use cases, XR technologies can provide concrete value in industrial settings.

To conclude, the adoption of XR in shipbuilding is at an early stage, but use cases for different sub technologies of XR have been successfully identified. Taking the liberty to make predictions—based on carefully reviewing the past decade of XR research on shipbuilding—we anticipate new research focusing on wide-scale deployments of established XR use cases within shipbuilding to emerge, while smaller scale piloting to shift focus towards more recent XR technologies, such as video passthrough. While artificial intelligence was not a notable emphasis in the research we reviewed, it seems evident that its role will grow in the future research on XR in shipbuilding—modern AI's powerful scene comprehension capability will be an enabler for novel XR applications and, conversely, XR is one mechanism for taking advantage of modern AI in the shipbuilding domain.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. MT: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review and editing. OH: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review and editing. TL: Funding acquisition, Supervision, Writing – original draft, Writing – review and editing, Conceptualization, Project administration. JJ: Supervision, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was done in the Business Finland funded project Virtual Sea Trial under Grant 7316/31/2023. The project is conducted collaboratively among the University of Turku, Novia University of Applied Sciences, Åbo Akademi University, the University of Oulu, as well as, industry partners and other international university partners.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Apple (2025). *Apple Vision Pro*. Available online at: https://www.apple.com/apple-vision-pro/ (Accessed October 15, 2025).

Aromaa, S., Aaltonen, I., Kaasinen, E., Elo, J., and Parkkinen, I. (2016). "Use of wearable and augmented reality technologies in industrial maintenance work," in *Proceedings of the 20th International Academic Mindtrek Conference* (New York, NY, USA: Association for Computing Machinery), 235–242. AcademicMindtrek '16. doi:10.1145/2994310.2994321

Bertagna, S., Braidotti, L., Bucci, V., and Marinò, A. (2025). An innovative methodology for enabling predictive maintenance of ship systems based on industry 4.0 technologies. *Procedia Comput. Sci.* 253, 2389–2398. doi:10.1016/j.procs.2025.01.299

Blanco-Novoa, O., Fernandez-Carames, T. M., Fraga-Lamas, P., and Vilar-Montesinos, M. A. (2018). A practical evaluation of commercial industrial augmented reality systems in an industry 4.0 shipyard. *IEEE Access* 6, 8201–8218. doi:10.1109/ACCESS.2018.2802699

Borczyk, A., and Singh, M. (2019). "Applications & advantages of employing digital ship design tools for newbuilding, retrofit and conversion projects," in *RINA, Royal Institution of Naval Architects - 19th International Conference on Computer Applications in Shipbuilding, ICCAS 2019 2*. Rotterdam: Royal Institute of Naval Architects.

Bradbeer, N. (2016). "Initial lessons from application of virtual reality to warship design," in *RINA, Royal Institution of Naval Architects - Warship 2016: Advanced Technologies in Naval Design, Construction, and Operation*. Bath: Royal Institute of Naval Architects.

Brisset, J., Bouju, Y., and Bourgeois, S. (2019). "Augmented reality for the visual inspection of pipes," in *RINA, Royal Institution of Naval Architects - 19th International Conference on Computer Applications in Shipbuilding, ICCAS 2019 1*.

Carter, R. (2006). Boat remains and maritime trade in the persian gulf during sixth and fifth millennia bc. *Antiquity* 80, 52–63. doi:10.1017/S0003598X0009325X

Cassar, C., Simpson, R. J., Bradbeer, N., and Thomas, G. (2019). "Integrating virtual reality software into the early stages of ship design," in *RINA, Royal Institution of Naval Architects - 19th International Conference on Computer Applications in Shipbuilding, ICCAS 2019 1*.

Chen, J., Wu, Q., Wang, G., Miao, P., Li, Y., and Wang, Z. (2021). "Application research of digital assembly system of marine turbocharger based on VR/AR,". *International conference on algorithms, high performance computing, and artificial intelligence (AHPCAI 2021)*. Editors L. Zhang, S. Chen, and M. AlShawabkeh (Sanya: Society of Photo-Optical Instrumentation Engineers (SPIE)), 12156, 1215610. doi:10.1117/12.2626469

Choi, S., and Park, J.-S. (2021). Development of augmented reality system for productivity enhancement in offshore plant construction. *J. Mar. Sci. Eng.* 9, 209. doi:10.3390/jmse9020209

Choi, T., and Seo, Y. (2020). A real-time physical progress measurement method for schedule performance control using vision, an ar marker and machine learning in a ship block assembly process. *Sensors* 20. doi:10.3390/s20185386

Choi, J., Son, M. G., Lee, Y. Y., Lee, K. H., Park, J. P., Yeo, C. H., et al. (2020). Position-based augmented reality platform for aiding construction and inspection of offshore plants. *Vis. Comput.* 36, 2039–2049. doi:10.1007/s00371-020-01902-9

COMPit (2026). About COMPit | CoMPit. Available online at: http://compit.hiper-conf.info/ (Accessed: March 2, 2026).

Diaz, R., Smith, K., Bertagna, S., and Bucci, V. (2023). Digital transformation, applications, and vulnerabilities in maritime and shipbuilding ecosystems. *Procedia Comput. Sci.* 217, 1396–1405. doi:10.1016/j.procs.2022.12.338

Fernandez, R. P., and Cosma, E. P. (2020). A future foretaste: shipbuilding industrial tendencies. *Int. J. Marit. Eng.* 162. doi:10.5750/ijme.v162iA4.1148

Fraga-Lamas, P., Fernández-Caramés, T., Blanco-Novoa, O., and Vilar-Montesinos, M. (2018). A review on industrial augmented reality systems for the industry 4.0 shipyard. *IEEE Access* 6, 13358–13375. doi:10.1109/ACCESS.2018.2808326

Garza Espinosa, J. A., Hernandez Contreras, M. A., Silva-Ortega, M., Hernandez, J. H., Valenzuela, V. G., Jimenez Gonzalez, S. M., et al. (2023). "Creation of a virtual reality environment for teaching applied to a catamaran-type ferry, detailing the engine room," in *2023 IEEE International Conference on Engineering Veracruz, ICEV 2023*. doi:10.1109/ICEV59168.2023.10329652

Gernez, E., Nordby, K., Archer Dreyer, S., Burås, T., and Fauske, J. E. (2023). How virtual reality is used in industrial maritime design processes: two case studies. *Ocean. Eng.* 283, 115091. doi:10.1016/j.oceaneng.2023.115091

Grazi, L., Feijoo Alonso, A., Gąsiorek, A., Pertusa Llopis, A. M., Grajeda, A., Kanakis, A., et al. (2025). Methodology and challenges of implementing advanced technological solutions in small and medium shipyards: the case study of the mari4_yard project. *Electronics* 14, 1597. doi:10.3390/electronics14081597

Han, Y.-S., Lee, J., Lee, J., Lee, W., and Lee, K. (2019). 3d cad data extraction and conversion for application of augmented/virtual reality to the construction of ships and offshore structures. *Int. J. Comput. Integr. Manuf.* 32, 658–668. doi:10.1080/0951192X.2019.1599440

Heimo, O. I., Sakari, L., Säntti, T., and Lehtonen, T. (2020). "Mixed reality for industry? An empirical user experience study," in *Intelligent Systems and Applications*. Editors Y. Bi, R. Bhatia, and S. Kapoor (Springer International Publishing), 241–253.

HIPER (2015). HIPER | high-performance marine vehicles. Available online at: http://www.hiper-conf.info/ (Accessed March 2, 2026).

Howard, S., Jang, R., O'Keeffe, V., Manning, K., Trott, R., Hordacre, A.-L., et al. (2023). Visual inspection with augmented reality head-mounted display: an australian usability case study. *Hum. Factors Ergonomics Manuf. & Serv. Industries* 33, 272–296. doi:10.1002/hfm.20986

HTC (2025). *HTC VIVE Standalone and PC VR headsets, VR glasses, AR, and MR*.

Jez, M., Fantoni, C., Keber, M., Rigutti, S., Straga, M., Miceu, P., et al. (2018). "A shared immersive virtual environment for improving ship design review," in *Technology and Science for the Ships of the Future - Proceedings of NAV 2018: 19th International Conference on Ship and Maritime Research*, 770–777. doi:10.3233/978-1-61499-870-9-770

Kim, H., Lee, J.-K., Park, J., Park, B.-J., and Jang, D.-S. (2002). Applying digital manufacturing technology to ship production and the maritime environment. *Integr. Manuf. Syst.* 13, 295–305. doi:10.1108/09576060210429748

Kim, D., Park, J., and Ko, K. H. (2018). Development of an ar based method for augmentation of 3d cad data onto a real ship block image. *Computer-Aided Des.* 98, 1–11. doi:10.1016/j.cad.2017.12.003

Kocak, S., and Helvacioglu, I. (2021). "Cooperation in shipbuilding projects from the perspective of main contractor candidate," in *Contract Management for Shipbuilding and Repair: Technical Perspective and Settlement of Legal Disputes*.

Kunkera, Z., Željković, I., Mimica, R., Ljubenkov, B., and Opetuk, T. (2024). Development of augmented reality technology implementation in a shipbuilding project realization process. *J. Mar. Sci. Eng.* 12, 550. doi:10.3390/jmse12040550

Lee, W.-H., Lee, K.-H., Lee, J.-M., and Nam, B.-W. (2020). Registration method for maintenance-work support based on augmented-reality-model generation from drawing data. *J. Comput. Des. Eng.* 7, 775–787. doi:10.1093/jcde/qwaa056

Li, H., Lendiuk, T., Grodskyi, S., Sachenko, A., and Brych, V. (2023). "Project management for cooperative development of welding safety training system using virtual reality," in *2023 IEEE 12th International Conference on Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications (IDAACS)*, 1, 1172–1177. doi:10.1109/IDAACS58523.2023.10348643

Liu, J., Wang, D., and Xiao, Y. (2021). "A method to visualize the physical assembly sequence of ship intermediate products with augmented reality (ar)," in *2021 International Conference on Computer, Internet of Things and Control Engineering (CITCE)*, 182–187. doi:10.1109/CITCE54390.2021.00043

Makkonen, T., Inkinen, T., and Saarni, J. (2013). Innovation types in the Finnish maritime cluster. *WMU J. Marit. Aff.* 12, 1–15. doi:10.1007/s13437-013-0039-4

Mankins, J. C. (1995). "Technology readiness levels: a white paper," in *Tech. rep., National Aeronautics and Space Administration (NASA), Advanced Concepts Office, Office of Space Access and Technology* (Washington, DC, USA).

Mann, S., and Wyckoff, C. (1991). Extended reality. *Tech. Rep. MIT*. MIT4-405.

Martin, J. (2019). *RINA, Royal Institution of Naval Architects - 19th International Conference on Computer Applications in Shipbuilding, ICCAS 2019 1. Virtual reality: Tool or toy for shipbuilding?*

Meta (2025). This is meta quest. Available online at: https://www.meta.com/fi/en/quest/ (Accessed December 1, 2025).

Microsoft (2024). Hololens 2 capabilities and solutions. Available online at: https://learn.microsoft.com/en-us/hololens/hololens-commercial-features (Accessed October 15, 2025).

Milgram, P., and Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Trans. Inf. Syst.* 77, 1321–1329.

Miličević, M., Vidović, M. S., Bonković, M., Kuzmanić, A., Ljubenkov, B., Mimica, R., et al. (2021). "Augmented reality for an efficient inspection of outfitting process in shipbuilding," in *2021 International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, 1–4. doi:10.23919/SoftCOM52868.2021.9559131

Nagano, M. (2015). "Digital mock-up and working simulation on mixed reality," in *RINA, Royal Institution of Naval Architects - International Conference on Computer Applications in Shipbuilding 2015, ICCAS 2015 - Papers 3*, 207–214. doi:10.3940/rina.iccas.2015.33

Oh, Y.-J., Park, K.-W., and Kim, E.-K. (2015). "Efficient 3d design drawing visualization based on mobile augmented reality," in *2015 17th International Conference on Advanced Communication Technology*, 568–573. doi:10.1109/ICACT.2015.7224925

O'Keeffe, V., Jang, R., Manning, K., Trott, R., Howard, S., Hordacre, A.-L., et al. (2024). Forming a view: a human factors case study of augmented reality collaboration in assembly. *Ergonomics* 67, 1828–1844. doi:10.1080/00140139.2024.2352733

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., et al. (2021). The prisma 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 372, n71. doi:10.1136/bmj.n71

Pedram, S., and Piatkowski, T. (2025). Exploring the potential of virtual reality (VR) in mental healthcare: a systematic literature review. *Virtual Real.* 29, 135. doi:10.1007/s10055-025-01181-6

Pérez Fernández, R., and Alonso, V. (2015). Virtual reality in a shipbuilding environment. *Adv. Eng. Softw.* 81, 30–40. doi:10.1016/j.advengsoft.2014.11.001

Piccininni, S., Dastan, M., Vangi, F., and Fiorentino, M. (2025). Magic: multi-user advanced graphic immersive configurator for sustainable customization of complex design products—a sailing yacht case study. *Future Internet* 17, 81. doi:10.3390/fi17020081

PW (2025). Piikkio works Oy | cabin modules. Available online at: https://www.piikkioworks.fi/ (Accessed November 10, 2025).

Pynn, W. (2017). "Minimising the designer/ end user knowledge gap using virtual reality," in *RINA, Royal Institution of Naval Architects - International Conference on Computer Applications in Shipbuilding, ICCAS 2017*, 1, 98–109.

Rajamäki, J., Tapola, M., Salonen, M., Heimo, O., and Lehtonen, T. (2025). Passthrough extended reality in maritime commissioning. *AHFE Open Access* 195. doi:10.54941/ahfe1006258

Rando, T. C., Preston, H. L., and Rossi, J. E. (2015). "Reducing shipbuilding touch labor costs with augmented reality," in *SNAME Maritime Convention and 5th World Maritime Technology Conference , D011S003R003*. doi:10.5957/WMTC-2015-236

Rauschnabel, P. A., Felix, R., Hinsch, C., Shahab, H., and Alt, F. (2022). What is xr? Towards a framework for augmented and virtual reality. *Comput. Hum. Behav.* 133, 107289. doi:10.1016/j.chb.2022.107289

Raymarine (2025). Marine Electronics products | RayMarine. Available online at: https://www.raymarine.com/en-us/our-products (Accessed: November 10, 2025).

Ren, M. (2019). Why technology adoption succeeds or fails: an exploration from the perspective of intra-organizational legitimacy. *J. Chin. Sociol.* 6, 21. doi:10.1186/s40711-019-0109-x

RINA (2025). Publications - Royal institution of naval architects - RINA. Available online at: https://rina.org.uk/publications/rina-transactions/ (Accessed November 1, 2025).

RINA (2026). The naval architect Jan/Feb 2026. Available online at: https://www.rina.org.uk/Naval-Architect-January-February-2026-Issue (Accessed March 2, 2026).

Rogers, E. (1962). *Diffusion of innovations*. New York, NY: Free Press of Glencoe.

Samala, A., Bojic, L., Rawas, S., Howard, N.-J., Pereira Coelho, D., Tsoy, D., et al. (2024). Extended reality for education: mapping current trends, challenges, and applications. *J. Pendidik. Teknol. Kejuru.* 7, 140–169. doi:10.24036/jptk.v7i3.37623

Sánchez-Sotano, A., Cerezo-Narváez, A., Abad-Fraga, F., Pastor-Fernández, A., and Salguero-Gómez, J. (2020). Trends of digital transformation in the shipbuilding sector *(intechopen)*. doi:10.5772/intechopen.91164

Schiavon, M., Keber, M., Cossutta, A., Zini, A., Jez, M., and Ambrosio, L. (2019). "Virtual reality in shipbuilding: Three use cases in a cruise ship design process," in *RINA, Royal Institution of Naval Architects - 19th International Conference on Computer Applications in Shipbuilding, ICCAS 2019 1*.

Šikić, G. (2017). "Using virtual reality paradigm to present ship structures in cad environment," in *RINA, Royal Institution of Naval Architects - International Conference on Computer Applications in Shipbuilding, ICCAS 2017*, 2, 18–25.

Stracke, C. M., Bothe, P., Adler, S., Heller, E. S., Deuchler, J., Pomino, J., et al. (2025). Immersive virtual reality in higher education: a systematic review of the scientific literature. *Virtual Real.* 29, 64. doi:10.1007/s10055-025-01136-x

Tsigkounis, K., Komninos, A., Politis, N., and Garofalakis, J. (2021). "Monitoring maritime industry 4.0 systems through vr environments," in *CHI Greece 2021: 1st International Conference of the ACM Greek SIGCHI Chapter* (New York, NY, USA: Association for Computing Machinery). CHI Greece.

UTU (2024). *Virtual Sea trial – software engineering laboratory*. Available online at: https://tt.utu.fi/sweng/virtual-sea-trial/ (Accessed December 1, 2025).

Valente, L., Feijó, B., Ribeiro, A., and Clua, E. (2018). Pervasive virtuality in digital entertainment applications and its quality requirements. *Entertain. Comput.* 26, 139–152. doi:10.1016/j.entcom.2018.02.006

van den Oever, F., Fjeld, M., and Sætrevik, B. (2024). A systematic literature review of augmented reality for maritime collaboration. *Int. J. Human–Computer Interact.* 40, 4116–4131. doi:10.1080/10447318.2023.2209838

Vukelic, G., Vizentin, G., and Hadžić, A. P. (2021). *Comparative swot analysis of virtual reality and augmented reality ship passenger evacuation technologies*, 68. Scientific Journals Maritime University of Szczecin, Zeszyty Naukowe Akademia Morska w Szczecinie. doi:10.17402/491

Wang, Y. (2017). Application of three - dimensional solid modeling of virtual reality technology in ship assembling. *Int. J. Mechatronics Appl. Mech.* 2017, 33–38. doi:10.17683/ijomam.issue1.5

Wang, J., Fan, X., Zhu, Y., Yang, X., and Yin, X. (2022). Cross-platform AR annotation for assembly-design communication in pipe outfitting. *Int. J. Adv. Manuf. Technol.* 121, 4981–4998. doi:10.1007/s00170-022-09637-8

Wang, Y., Yin, X., Yang, X., Luo, X., and Fan, X. (2024). "Cognitive load evaluation of outfitting AR visual information,". *Third International Conference on New Materials, Machinery, and Vehicle Engineering (NMMVE 2024)*. Editors J. Xu and J. P. Davim (Bucharest: Publishing House: CEFIN), 13420, 134201C. doi:10.1117/12.3055017

Wärtsilä (2025). Marine waste & wastewater treatment. *Syst. Every Type Ship*. Available online at: https://www.wartsila.com/marine/products/waste-and-wastewater-treatment (Accessed November 10, 2025).

Zakharov, R. O. (2023). "Analysis of the problems of using vr technology in shipbuilding design," in *2023 Seminar on Information Computing and Processing (ICP)*, 235–238. doi:10.1109/ICP60417.2023.10397378

Zhenghong, L., Jian, L., Huiliang, Z., and Jie, L. (2020). Prediction of graphic interaction time of virtual reality system based on improved fitts' law. *Trait. Du. Signal* 37, 227–234. doi:10.18280/ts.370208