Identification and Prioritization of Industry 4.0 Technologies in Maritime Industries Using Best-Worst Method (BWM)

Hamid Ameri[1] | Vahid Ameri[2*] | Mojtaba Abbaspour[3]

Article Type:
Research Article

Hamid Ameri
M.A. in Marine Engineering, Malek Ashtar University of Technology, Shahin Shahr, Iran.
E-mail: hamid.ameri.3847@gmail.com

Vahid Ameri
Corresponding Author, M.A. Student in Marketing Management, Faculty of Management and Accounting, Farabi College, Tehran University, Qom, Iran.
E-mail: vahid.ameri@ut.ac.ir

Mojtaba Abbaspour
Assistant Professor, Department of Maritime Economics and Management, Khorramshahr University of Marine Science and Technology, Khorramshahr, Iran
E-mail: M.abbaspour@kmsu.ac.ir

Spring & Summer (2025) 2(1): 157-174

Received: 18 March 2025
Revised: 12 April 2025
Accepted: 16 April 2025
Available Online: 22 April 2025

ABSTRACT

The Fourth Industrial Revolution (Industry 4.0) has provided significant opportunities to improve performance and productivity in maritime industries through emerging technologies. However, the multiplicity and diversity of these technologies have turned their selection and prioritization into a fundamental challenge for decision-makers. This research study aims to identify and prioritize key Industry 4.0 technologies in maritime industries. Through conducting a systematic literature review and interviews with 15 industry experts, 59 applications within 12 key technologies were identified. Then, using the Best-Worst Method (BWM) of multi-criteria decision-making, the relative importance of technologies and their applications were determined. The results showed that Digital Twin Systems with a weight of 20.02 is the most important technology, followed by Robotics and Automation with a weight of 16.11, and Artificial Intelligence (AI) and Machine Learning with a weight of 12.08. Among the applications, operation optimization through scenario testing, autonomous vehicle guidance in port areas, and staff training with virtual models obtained the highest priorities. By providing a systematic framework for technology prioritization, this research can assist decision-makers in maritime industry to allocate optimal resources and reduce investment risks.

KEYWORDS

Artificial Intelligence, Digital Twin Systems, Fourth Industrial Revolution, Maritime Industries, Robotics and Automation.

Cite this article: Ameri, H., Ameri, V. and Abbaspour, M. (2025). Identification and Prioritization of Industry 4.0 Technologies in Maritime Industries Using Best-Worst Method (BWM). *Journal of Knowledge Economy Studies (JKES)*, 2(1), 157-174.

DOI: http//doi.org//10.22034/kes.2025.2056235.1049 **Publisher:** Hazrat-e Masoumeh University

Introduction

The Fourth Industrial Revolution, as a significant transformation in the digital era, is characterized by the integration of emerging technologies into industrial processes. This revolution, also known as Industry 4.0, is founded on the integration of cyber-physical systems, Internet of Things (IoT), cloud computing, Artificial Intelligence (AI), and other advanced technologies (Rüßmann et al., 2015). The concept of Industry 4.0, first introduced in Hanover Fair in Germany in 2011, has now become the dominant paradigm in the digital transformation of various industries, offering a novel approach to optimizing production processes and services (Berns et al., 2017). This revolution emerged with the aim of creating smart factories, flexible manufacturing, and supply chain optimization, and has rapidly expanded to other industrial domains.

Meanwhile, maritime industries, as one of the main pillars of the global economy, face numerous challenges in productivity, competitiveness, and sustainability. Statistics from the World Trade Organization show that more than 90 percent of global trade volume is conducted through maritime transport, with an annual growth rate of 3 to 4 percent (Yang et al., 2018). This enormous volume of commercial exchanges, accompanied by increasing competitive pressures, stringent environmental requirements, the need to reduce fuel consumption and emissions, and the necessity to enhance operational safety, requires new approaches in management and operations (Acciaro et al., 2018).

Emerging Industry 4.0 technologies offer significant potential to address these challenges. Studies indicate that implementing these technologies can lead to a 15 to 20 percent increase in operational productivity and a 30 percent reduction in maintenance costs (Chu et al., 2018). For example, the use of automated systems in port operations, AI in predicting vessel arrival times, IoT in equipment monitoring, and digital twin systems in operating simulation has created a fundamental transformation in the efficiency and effectiveness of the operations. Additionally, the use of augmented reality-based technologies in employee training and maintenance, and the application of Blockchain in supply chain management, have opened new horizons in the management of this industry.

The successful experience of leading global ports in implementing Industry 4.0 technologies demonstrates the significant potential of this digital transformation. For instance, the Port of Rotterdam, by implementing digital twin systems, has reported a 25 percent increase in operational productivity (PTI, 2019). The Port of Singapore, with the implementation of advanced automation projects and autonomous vehicles, has achieved a 20 percent reduction in container loading and unloading time (Woo, 2018). The Port of Hamburg has implemented an integrated traffic management and pollution control system using 5G and IoT (Krantz, 2017).

However, the multiplicity and diversity of available technologies have made their selection and prioritization a fundamental challenge for decision-makers. The high initial investment costs, which can sometimes reach hundreds of millions of dollars, limitations in human and financial resources, technical complexities of implementation, cyber-security issues, and the need for extensive workforce training, double the importance of making the right decisions in technology selection. This issue requires a systematic approach to identify and prioritize various technologies (Boyes et al., 2016; Vanelslander et al., 2019).

A review of the literature shows that previous studies have mainly focused on technical aspects or case applications (Xisong et al., 2013; Jardas et al., 2018). Some studies have examined the application of specific technologies such as AI or IoT in specific sectors of maritime industries (Kim, 2017; Rodič, 2017), while others have only addressed technical aspects of their implementation (Lu, 2017; Pérez-Lara et al., 2018). Thus, there is a significant gap in comprehensive decision-making frameworks for selecting and prioritizing these technologies. This research gap reveals the necessity of adopting a scientific and systematic approach to analyze and prioritize emerging Industry 4.0 technologies in maritime industries.

Accordingly, the present research has been conducted with the aim of analyzing and prioritizing emerging Industry 4.0 technologies in maritime industries. This study, utilizing the Best-Worst Multi-Criteria Decision-Making method, provides a systematic approach for evaluating and ranking these technologies. The Best-Worst method was chosen due to its capabilities in consistent pairwise comparisons, reducing the number of comparisons needed, and reliable results. The findings of this research study can serve as a scientific framework for decision-making in selecting and implementing Industry 4.0 technologies in maritime industries.

Literature Review

Industry 4.0

Industry 4.0 is a comprehensive concept that encompasses a set of emerging technologies for digitizing and creating intelligent industrial processes. This industrial revolution, first introduced in Hanover Fair in Germany in 2011, has created a fundamental transformation in the way products and services are produced and delivered by focusing on the integration of physical and digital systems. Boyes et al. (2016) in their comprehensive study on the impact of Industry 4.0 on organizational performance demonstrated that implementing these technologies can lead to a 25 to 35 percent increase in operational productivity.

Li (2018) showed that Industry 4.0, by integrating advanced technologies such as AI, IoT, cloud computing, and digital twin systems, provides the possibility of creating fully intelligent production environments. These intelligent environments are capable of making automated decisions and optimizing processes using real-time data. Xiu and Chen (2021) found that using Industry 4.0 technologies can reduce the operational costs by up to 20 percent and increase the production flexibility by up to 50 percent.

Tang et al. (2022) examined the impact of Industry 4.0 on global supply chain. The findings showed that this industrial revolution can increase supply chain flexibility by up to 45 percent through digitizing processes, improving transparency, and increasing traceability. Additionally, their findings showed that implementing Industry 4.0

technologies can reduce response time to market changes by up to 35 percent and improve demand forecasting accuracy by up to 40 percent.

Key Technologies of Industry 4.0

Internet of Things (IoT), as one of the main foundations of Industry 4.0, plays a central role in making industries intelligent. Jayavardhana et al. (2013) showed that IoT, through a network of sensors and communication systems, enables real-time data collection and intelligent control of processes. This technology provides a comprehensive view of the operational status of systems by creating connections between different equipment. Wang et al. (2018) found that using IoT in industrial environments can lead to a 40 percent reduction in equipment downtime and a 25 percent increase in energy efficiency.

AI and Machine Learning are key technologies of Industry 4.0. Kosova and Ünver (2022) demonstrated that these technologies, using advanced algorithms, are capable of analyzing massive volumes of industrial data and identifying complex patterns in industrial processes. According to existing studies, the use of AI in industrial processes can lead to significant improvements in operational efficiency and equipment failure prediction.

Blockchain, as another key technology of Industry 4.0, has created a fundamental transformation in managing industrial processes and supply chains. Studies by Harsha Vardhan et al. (2023) and Turgay and Erdoğan (2023) showed that this technology provides the possibility of transparent and reliable process tracking by creating a decentralized and immutable record system. This technology helps improve transaction speed by eliminating intermediaries and automating verification processes.

Digital Twin Systems are also recognized as one of the most advanced technologies of Industry 4.0. Liu (2023) and Tao et al. (2018) concluded that these systems provide the possibility of simulation and optimization of processes before their implementation by creating a virtual version of the physical environment. These systems can help reduce product design time and development costs and provide the opportunity to test different scenarios in a virtual environment without any risk.

Applications of Industry 4.0 in Maritime Industries

In the maritime industry sector, Industry 4.0 technologies have found extensive applications. Yang et al. (2018) argued that using IoT in port management can lead to a 35 percent improvement in loading and unloading operations efficiency. This improvement is achieved through real-time monitoring of equipment, container tracking, and intelligent port traffic management. Woo (2018) investigated the application of AI in maritime fleet management. He found that this technology can reduce the fuel consumption by up to 15 percent and increase the operational safety by up to 40 percent.

Chu et al. (2018) conducted a comprehensive review of automated ports. They found that using smart cranes and autonomous vehicles can increase the operational productivity by up to 45 percent. In this regard, the Port of Singapore, as one of the pioneers in port automation, has been able to reduce container loading and unloading time by up to 30 percent by employing advanced robotic systems. Kamolov and Park

(2019) explored the automated ship guidance systems and found that these systems can reduce the berthing operation time by up to 25 percent and improve operational safety by up to 50 percent.

Digital Twin Systems have various applications in maritime industries. Zhang and Chen (2020) argued that these systems provide the opportunity to optimize operations before implementation by simulating the performance of ships and port equipment in a virtual environment. Their research showed that using Digital Twins in port operations planning can lead to a 20 percent reduction in waiting times and a 35 percent improvement in resource allocation.

Blockchain has also created a fundamental transformation in maritime supply chain management. Li (2018) examined Blockchain applications in maritime transport. He concluded that this technology can reduce the document processing time by up to 70 percent and administrative costs by up to 40 percent. Additionally, the use of smart contracts in port operations provides the possibility of automating business processes and reducing human errors.

A review of previous research shows that despite the existence of extensive studies in the field of Industry 4.0 and its applications in maritime industries, there is a significant gap in prioritizing and selecting these technologies. Most studies conducted have either examined a specific technology on a case-by-case basis (Kim, 2017; Rodič, 2017) or have only focused on technical aspects of implementation (Lu, 2017; Pérez-Lara et al., 2018). Meanwhile, decision-makers in maritime industries need a comprehensive framework for evaluating and prioritizing these technologies. High investment costs, technical complexities of implementation, and resource limitations double the importance of making the right decisions in selecting the appropriate technologies. Therefore, the present research study has been conducted with the aim of filling this research gap and providing a systematic framework for prioritizing Industry 4.0 technologies in maritime industries.

Table 1.

Key Studies and Identified Industry 4.0 Technologies from Systematic Literature Review

Study	Focus Area	Technologies Identified
Rüßmann et al. (2015)	General framework for Industry 4.0	AI, IoT, Cloud Computing, Digital Twin Systems, Robotics
Boyes et al. (2016)	Cyber-security in maritime	Cyber-security, IoT, Cloud Computing
Yang et al. (2018)	Smart ports	IoT, Big Data Analytics, Digital Twin Systems
Vanelslander et al. (2019)	Maritime innovation	Blockchain, Automation, Robotics
Woo (2018)	Port automation	Robotics and Automation, AI
Li (2018)	Blockchain applications	Blockchain, Smart Asset Management
Chu et al. (2018)	Automated ports	Robotics, AI, IoT
Xiu & Chen (2021)	Smart manufacturing	Digital Twin Systems, 3D Printing, AR
Tang et al. (2022)	Supply chain flexibility	Blockchain, Cloud Computing, Big Data
Tao et al. (2018)	Digital Twin applications	Digital Twin Systems, IoT, AR
Kim (2017)	Cyber-physical systems	IoT, Cyber-security, Cloud Computing
Zhang & Chen (2020)	Smart ports	Digital Twin Systems, Big Data Analytics

(Source: Researcher's Findings)

Methodology

The philosophy underpinning this research study is pragmatism, which, as a practical philosophy, has special importance in applied research. The present study is descriptive in terms of its purpose and cross-sectional in terms of time horizon. Additionally, in terms of orientation, it is considered as an applied research study. The research approach is mixed (qualitative-quantitative) and has been conducted in two stages. In the first stage, with a qualitative approach, through conducting a systematic literature review and semi-structured interviews with experts, the technologies and applications of Industry 4.0 in maritime industries were identified. In the second stage, with a quantitative approach, the Best-Worst Multi-Criteria Decision-Making method was used to rank and determine the relative importance of each technology and its application.

The statistical population of the study includes specialists and experts in the country's maritime industries. Sampling was done using a purposeful method and 15 experts including 12 middle managers of maritime industries and 3 university professors who work as consultants in this industry were selected. The criterion for selecting the experts was having at least 6 years of experience in maritime industries and familiarity with the concepts and applications of Industry 4.0.

In the qualitative stage, a systematic literature review was conducted to extract articles related to Industry 4.0 technologies in maritime industries, identifying 59 applications. These applications were statistically validated using a T-test to confirm their relevance to maritime industries, retaining only those with statistical significance ($p < 0.05$). Following the literature review and statistical validation, semi-structured interviews were conducted with experts. An interview protocol was used to guide the interviews, and interviewees were asked to validate and assess the applications of Industry 4.0 identified from the literature. To ensure the reliability of the analysis, the interview data was reviewed by two independent researchers, and an agreement coefficient of over 70 percent was obtained, indicating appropriate reliability.

In the quantitative stage, the Best-Worst Multi-Criteria Decision-Making method was used to rank and determine the relative importance of tools and applications. This method requires fewer pairwise comparisons compared to other multi-criteria decision-making methods such as AHP, and its results have higher reliability (Rezaei, 2016). The number of pairwise comparisons required in this method is calculated from the formula 2*m-3.

The steps of this method are as follows:

Step One: In this step, a set of decision-making indicators, which includes 59 tools and applications of Industry 4.0 in maritime industries, was determined.

Step Two: In this step, based on the expert opinion, the best and worst criteria among the factors were determined.

Step Three: The preference of the best indicator relative to other indicators is done on a scale of 1 to 9, which is shown as a preference vector in the form of $AB = (a_{b_1}, a_{b_2}, ..., a_{b_n})$. In the mentioned vector, a_{b_j} represents the preference of the best criterion (b) over criterion (j), and it is clear that $a_{bb} = 1$.

Step Four: The preference of all indicators relative to the worst option is specified on a scale of 1 to 9. The preference vector of other indicators to the worst indicator is represented as $A_W = (a_{1W}, a_{2W}, ..., a_{nW})$. a_{jW} represents the preference of indicator (j) over the worst indicator (w), and it is clear that $a_{WW} = 1$.

Step Five: In this step, since the questionnaire has been distributed among 15 people, it is necessary to take an average, and subsequent calculations were performed on this average.

Step Six: The optimal weight values were determined. Thus, the model can be formulated as follows:

$$\begin{aligned} &\min max_j \left(\left|\frac{WB}{Wj} - a_{Bj}\right|, \left|\frac{wj}{Ww} - a_{jw}\right|\right) \\ &\sum_{j}^{s.t.} wj = 1 \\ &wj \geq 0 \; for \; all \; j \end{aligned} \tag{1}$$

Furthermore, the above model can be converted to the following model:

$$\begin{aligned} &\min \;\; \xi \\ &s.t. \\ &\left|\frac{WB}{Wj} - a_{Bj}\right| \leq \xi, \text{for all j} \\ &\left|\frac{wj}{Ww} - a_{jw}\right| \leq \xi, \text{for all j} \\ &\sum_{j}^{w} wj = 1 \\ &wj \geq 0 \; for \; all \; j \end{aligned} \tag{2}$$

The linear function model is presented as follows (Rezaei, 2016) and is also used in this article:

$$\begin{aligned} &\min \;\; \xi \\ &s.t. \\ &\left|w_B - a_{Bj} w_j\right| \leq \boldsymbol{\xi}, \text{for all } j \\ &\left|w_j - a_{jw} w_w\right| \leq \boldsymbol{\xi}, \text{for all } j \\ &\sum_{j}^{w} wj = 1 \\ &wj \geq 0 \; for \; all \; j \end{aligned} \tag{3}$$

Finally, by solving the above model, the optimal weight values and inconsistency rate were obtained.

Findings

Through conducting a systematic literature review (as summarized in Table 1), we identified emerging technologies of Industry 4.0 and their applications in maritime industries. This review yielded 12 key technology categories and their potential applications. To validate these findings and enrich the framework, the interviews were conducted with 12 middle managers of maritime businesses and 3 academic experts who worked as consultants in these fields. The expert consultation confirmed the relevance of 12 technologies identified from the literature and validated 59 specific applications of these technologies in maritime contexts.

The technologies identified through systematic literature review and validated by experts were categorized as follows: Internet of Things (IoT), Blockchain, AI and Machine Learning, Robotics and Automation, Augmented Reality, 3D Printing, Cloud Computing, Smart Asset Management, Cybersecurity, Environmental Monitoring, Big Data Analytics, and Digital Twin Systems.

Initially, the main technologies and their applications were identified and categorized. The results of the T-test are presented in Table 2. Accordingly, the final framework based on the main technologies and their related applications is as follows:

Internet of Things (IoT): By examining the concepts obtained from the analysis of the interviews, the first key technology was the Internet of Things. This technology provides the possibility of real-time data collection and intelligent monitoring by creating integrated networks of sensors and connected equipment. Based on the interviews, its most important applications include tracking and locating containers, monitoring port equipment, managing ship traffic, and collecting environmental data. For example, one expert stated: *"IoT provides real-time monitoring of equipment and container conditions, which is essential for optimizing port operations".*

Blockchain: The second key technology identified was blockchain, which provides the capability for transparency and traceability in transactions. According to experts, the most important applications of this technology include increasing transparency in the supply chain, facilitating information exchange between stakeholders, reducing intermediary intervention, and increasing security in transactions. One expert stated: *"Blockchain, by eliminating intermediaries and creating transparency, can transform business processes in the maritime industry".*

Artificial intelligence (AI): The third important technology is AI and machine learning. This technology plays an important role in operations optimization with its ability to analyze complex data and learn from patterns. The most important identified applications include real-time ship arrival prediction (enabling precise scheduling through advanced algorithms), analyzing maritime traffic risks, predictive fuel optimization using AI algorithms (reducing fuel use by up to 15% through real-time predictive models), and managing intelligent terminals. According to one specialist: *"Artificial intelligence, with accurate prediction of ship arrival times, provides the possibility for optimal operations planning".*

Robotics and Automation: This technology plays an important role in increasing productivity and safety with the aim of automating operations. Its main applications include automatic guidance of vehicles in the port area, preventive monitoring and maintenance of equipment, automation of operational processes, and development of automated cranes. Experts believe: *"Port automation, in addition to increasing productivity, helps reduce human error and increase safety".*

Augmented Reality: Studies show that augmented reality, with the ability to combine the real and virtual worlds, has various applications in maritime industries. The most important applications identified for this technology include employee training, assistance in ship berthing operations, equipment inspection and maintenance, and digitization of inspection processes. One expert noted: "*Augmented reality provides the possibility for practical and interactive training for employees, which is much more effective than traditional methods".*

3D Printing: This technology has created a transformation in maintenance and repairs with the possibility of custom production of parts. Based on the interviews, its main applications include producing spare parts of the ship, manufacturing ship molds, repairing and rebuilding parts, rapid prototyping, and localizing parts production. Experts believe: *"3D printing can significantly reduce the time and cost of supplying spare parts".*

Cloud Computing: This technology provides the necessary software infrastructure for data processing and storage. Its main applications include data sharing between stakeholders, managing port information, networking for design and production, and planning joint operations. One specialist stated: "Cloud Computing provides the possibility of integrated access to data and effective collaboration between stakeholders".

Smart Asset Management: The eighth identified technology is Smart Asset Management, which plays an important role in optimizing the performance of equipment. The main applications of this technology include monitoring the condition of port infrastructure, predicting repairs, reducing maintenance costs, and improving the life cycle of ships. One expert emphasized: *"Smart asset management prevents unwanted stoppages by timely predicting maintenance needs".*

Cybersecurity: In the digital age, cybersecurity has become one of the most essential technologies. Based on the interviews, its most important applications are protecting information systems, managing cyber risks, protecting vital infrastructure, and reducing risk, and increasing safety. According to specialists: *"With increased system connectivity, cybersecurity has become a strategic priority".*

Environmental Monitoring: This technology has been developed with the aim of monitoring and reducing environmental impacts. Its main applications include monitoring environmental conditions, reducing carbon emissions, monitoring hazardous material leaks, and identifying and reducing energy waste. Experts believe: *"Environmental monitoring plays a key role in achieving sustainability goals and reducing pollution".*

Big Data Analytics: Change to: The eleventh identified technology is big data analytics, which provides the possibility of extracting insights from massive volumes of data. Its most important applications include historical ship arrival trend analysis (identifying patterns in past arrival data), analyzing maritime traffic risks, fuel efficiency analysis using historical data (leveraging large datasets to identify fuel-saving opportunities), controlling ship performance, preventive maintenance, and data-based decision-making. One specialist stated: *"Big data analytics provides the possibility for more accurate and faster decision-making".*

Digital Twin Systems: Change to: The last and most important identified technology is Digital Twin Systems, which provide the possibility of accurate simulation of physical systems in the digital world. The main applications of this technology include ship performance simulation for operational scenarios (e.g., optimizing navigation or cargo handling), ship performance simulation for design validation (e.g., testing ship designs before construction), training employees with virtual models, optimizing operations by testing different scenarios and predicting maintenance needs. According to one expert: *"Digital Twin Systems, with accurate simulation of operations, provide the possibility of process optimization without the risks of the real world"* (see Table 2).

Table 2.
T-test

Tools	Applications	Mean	Standard Deviation	t	Sig.
Internet of Things (IoT)	Container tracking and locating	3.80	1.014	3.055**	0.009
	Port equipment monitoring	4.13	0.834	5.264**	0.000
	Ship traffic management	3.87	0.834	4.026**	0.001
	Environmental and oceanography data collection	3.93	0.884	4.090**	0.001
	Controlling and monitoring of port facilities	3.40	0.507	3.055**	0.009
	Decision-making using automatic data	3.93	0.884	4.090**	0.001
Blockchain	Increasing transparency in supply chain	4.67	0.488	13.229**	0.000
	Facilitating information exchange between stakeholders	4.53	0.640	9.280**	0.000
	Reducing intermediary intervention	4.13	0.834	5.264**	0.000
	Enhanced security in transactions	3.87	0.834	4.026**	0.001
	Information management between stakeholders	3.60	1.056	2.201**	0.045
Artificial Intelligence and Machine Learning	Real-time ship arrival prediction	4.27	0.799	6.141**	0.000
	Maritime traffic risk analysis	4.00	1.000	3.873**	0.002
	Predictive fuel optimization using AI algorithms	4.67	0.617	10.458**	0.000
	Intelligent terminal management	4.33	0.816	6.325**	0.000
Robotics and Automation	Automatic control of port cranes	3.07	1.163	0.222	0.827
	Automatic guidance of vehicles in port area	4.60	0.632	9.798**	0.000
	Preventive monitoring and maintenance of equipment	3.93	0.884	4.090**	0.001
	Automation of operational processes	4.20	0.775	6.00**	0.000
	Development of automated access bridges	4.07	0.799	5.172**	0.000
	Improving operations with autonomous ships	4.47	0.640	8.876**	0.000
Augmented Reality	Employee training	4.67	0.617	10.458**	0.000
	Assistance in ship berthing operations	3.80	1.014	3.055**	0.009
	Equipment inspection and maintenance	4.60	0.632	9.798**	0.000
	Digitization of inspection processes	4.33	0.816	6.325**	0.000
3D Printing	Production of spare parts of the ships	3.07	1.335	0.193	0.849
	Manufacturing ship molds	4.40	0.910	5.957**	0.000
	Repair and rebuilding of parts	4.47	0.640	8.876**	0.000
	Rapid prototyping with reduced time and cost	4.53	0.640	9.280**	0.000
	Localization of parts production	4.47	0.640	8.876**	0.000
Cloud Computing	Data sharing between stakeholders	3.20	0.414	1.871	0.082
	Port information management	4.33	0.816	6.325**	0.000
	Networking for design and production	4.67	0.617	10.458**	0.000

Tools	Applications	Mean	Standard Deviation	t	Sig.
	Planning of joint operations	3.80	1.014	3.055**	0.009
	Collaboration between shipping lines and terminals	3.87	0.834	4.026**	0.001
Smart Asset Management	Monitoring the condition of port infrastructure	4.00	1.000	3.873**	0.002
	Predicting repairs	4.27	0.799	6.141**	0.000
	Reducing maintenance costs	4.47	0.640	8.876**	0.000
	Improving ship life cycle	4.33	0.816	6.325**	0.000
Cyber-security	Protection of information systems	3.93	0.884	4.090**	0.001
	Managing cyber risks	4.67	0.617	10.458**	0.000
	Protection of vital infrastructure	4.47	0.640	8.876**	0.000
	Risk reduction and safety improvement	4.60	0.632	9.798**	0.000
Environmental Monitoring	Monitoring environmental conditions	3.27	0.458	2.256**	0.041
	Reducing carbon emissions	4.47	0.640	8.876**	0.000
	Using low-carbon fuels	3.13	1.457	0.354	0.728
	Monitoring hazardous material leaks	4.60	0.632	9.798**	0.000
	Identifying and reducing energy waste	4.27	0.799	6.141**	0.000
Big Data Analytics	Historical ship arrival trend analysis	3.07	1.335	0.193	0.849
	Analyzing maritime traffic risk	3.67	1.047	2.467**	0.027
	Fuel efficiency analysis using historical data	4.53	0.640	9.280**	0.000
	Controlling the ship performance	4.27	0.799	6.141**	0.000
	Preventive maintenance	4.47	0.640	8.876**	0.000
	Data-based decision-making	4.60	0.632	9.798**	0.000
Digital Twin Systems	Ship performance simulation for operational scenarios	4.53	0.640	9.280**	0.000
	Employee training with virtual models	4.67	0.617	10.458**	0.000
	Operations optimization by testing different scenarios	4.73	0.458	14.666**	0.000
	Predicting maintenance needs	4.53	0.640	9.280**	0.000
	Ship performance simulation for design validation	4.47	0.516	11.00**	0.000

** Significant at 0.05 level

(Source: Researcher's Findings)

Change to: Based on the results of statistical analysis in Table 2, out of the total 59 identified applications, 5 applications were eliminated due to lack of statistical significance ($p>0.05$): 'Automatic control of port cranes' (t=0.222, Sig.=0.827), 'Use of low-carbon fuels' (t=0.354, Sig.=0.728), 'Historical ship arrival trend analysis' (t=0.193, Sig.=0.849), 'Production of spare parts of the ships' (t=0.193, Sig.=0.849), and 'Data sharing between stakeholders' (t=1.871, Sig.=0.082). The remaining 54 applications proceeded to the next stage. In the next stage, the Best-Worst method was used to determine the relative importance and weight of each technology and its related applications. First, the weight of the applications for each technology was determined and then compared with each other. The final weight of the applications was calculated from the product of the two obtained weights. Additionally, the inconsistency rate for all weights was calculated and confirmed. The results are shown in Table 3.

Table 3.
The Ranking of Applications

Tools	Tool Weight	Applications	Application Weight	Final Weight	Rank
Internet of Things (IoT)	4.83	Container tracking and locating	9.80	47.334	44
		Monitoring Port equipment	32.68	143.4652	22
		Ship traffic management	13.07	157.8856	19
		Environmental and oceanography data collection	19.61	315.9171	9
		Controlling and monitoring port facilities	5.23	36.087	47
		Decision-making using automatic data	19.61	105.3057	29
		Increasing transparency in supply chain	40.37	177.2243	17

Tools	Tool Weight	Applications	Application Weight	Final Weight	Rank
Blockchain	4.39	Facilitating information exchange between stakeholders	24.60	297.168	10
		Reducing intermediary interventions	16.40	264.204	11
		Enhanced security in transactions	12.30	84.87	33
		Information management between stakeholders	6.30	33.831	48
Artificial Intelligence and Machine Learning	12.08	Real-time ship arrival prediction	17.24	208.2592	16
		Maritime traffic risk analysis	10.34	166.5774	18
		Predictive fuel optimization using AI algorithms	46.55	321.195	8
		Intelligent terminal management	25.86	138.8682	23
Robotics and Automation	16.11	Automatic guidance of vehicles in port area	41.61	670.3371	2
		Preventive monitoring and maintenance of equipment	5.78	39.882	46
		Automation of operational processes	16.18	86.8866	32
		Development of automated access bridges	12.13	48.7626	43
		Improving operations with autonomous ships	24.27	73.7808	34
Augmented Reality	6.90	Employee training	48.46	334.374	6
		Assistance in ship berthing operations	9.23	49.5651	42
		Equipment inspection and maintenance	25.38	102.0276	30
		Digitization of inspection processes	16.92	51.4368	41
3D Printing	5.37	Manufacturing ship molds	10.34	55.5258	40
		Repairing and rebuilding parts	17.24	92.5788	31
		Rapid prototyping with reduced time and cost	46.55	249.9735	12
		Localization of parts production	25.86	138.8682	23
Cloud Computing	4.02	Port information management	0.30	1.203	52
		Networking design and production	0.51	2.0502	51
		Planning joint operations	0.07	0.2814	54
		Collaboration between shipping lines and terminals	0.12	0.4824	53
Smart Asset Management	3.04	Monitoring the condition of port infrastructure	9.52	28.9407	49
		Predicting repairs	23.80	72.352	35
		Reducing maintenance costs	42.85	130.264	25
		Improving ship life cycle	23.80	72.352	35
Cyber-security	8.05	Protecting the information systems	8.13	65.4465	38
		Managing cyber risks	47.15	379.5575	5
		Protecting vital infrastructure	17.88	143.934	21
		Risk reduction and safety improvement	26.82	215.901	15
Environmental Monitoring	2.44	Monitoring environmental conditions	6.57	16.0308	50
		Reducing carbon emissions	27.63	67.4172	37
		Monitoring hazardous material leaks	47.36	115.5584	28
		Identifying and reducing energy waste	18.42	44.9448	45
Big Data Analytics	9.67	Analyzing maritime traffic risks	5.78	55.8926	39
		Fuel efficiency analysis using historical data	24.27	234.6909	14
		Controlling the ship performance	12.13	117.2971	27
		Preventive maintenance	16.18	156.4606	20
		Data-based decision-making	41.61	402.3687	4
Digital Twin Systems	20.02	Ship performance simulation for operational scenarios	16.40	328.328	7
		Employee training with virtual models	24.60	492.492	3
		Optimizing operations by testing different scenarios	40.38	808.4076	1
		Predicting maintenance needs	12.30	246.246	13
		Ship performance simulation for design validation	6.30	126.126	26

(Source: Researcher's Findings)

Based on the results in Table 3, Digital Twin Systems with a weight of 20.2 is the most important technology (tool) of the Fourth Industrial Revolution in maritime industries. The next technologies in order are Robotics and Automation with a weight of 16.11, Artificial Intelligence and Machine Learning with a weight of 12.08, and finally Environmental Monitoring with a weight of 2.44. Overall, the top-ranked application belongs to Optimizing Operations by Testing Different Scenarios in Digital Twin Systems technology. Additionally, the application of Automatic Guidance of Vehicles in Port Area in Robotics and Automation technology and Employee Training with Virtual Models in Digital Twin Systems technology ranked as the second and third, respectively. Planning Joint Operations and Collaboration between Shipping Lines and Terminals occupied the last two positions.

Discussion and Conclusion

Discussion

The maritime industry in the present era has different conditions. Some specialists in this industry consider the current environment as turbulent and full of continuous changes, where success requires new and up-to-date technologies (Ilias et al., 2023). This aligns with the concept of a VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) environment, where leadership and decision-making require specific cognitive skills and strategic approaches to navigate effectively through uncertainties (Hafezniya & Ansari, 2024). The emergence of advanced Industry 4.0 technologies, along with increasing competitive pressures, stringent environmental requirements, the need to reduce fuel consumption, and the necessity to enhance operational safety, has caused maritime industries to be in a state of high change both in terms of internal processes and macro-environmental forces (Ilias et al., 2023). The importance of applying emerging technologies in various transportation sectors, including intelligent transportation, has also been emphasized by Fasanghari and Asarian (2024). They found that the fifth-generation technologies can lead to significant improvements in efficiency and safety of transportation systems.

Additionally, the experience of leading global ports shows that implementing these technologies can lead to a 15 to 20 percent increase in operational productivity and a 30 percent reduction in maintenance costs (Ilias et al., 2023).

Based on studies and interviews conducted with industry experts, out of a total of 59 applications identified in the form of 12 key technologies, 54 applications were selected for final analysis and ranking. The results of the statistical analysis showed that Digital Twin Systems with a weight of 20.02 is the most important technology of the Fourth Industrial Revolution in maritime industries, followed by Robotics and Automation with a weight of 16.11, and Artificial Intelligence and Machine Learning with a weight of 12.08.

The analysis of the prioritization results reveals several significant patterns. First, there is a clear preference for technologies that enable operational simulation and automation, with Digital Twin Systems (20.02) and Robotics and Automation (16.11) receiving the highest weights. This suggests that maritime industry stakeholders prioritize technologies that can reduce the operational risk while increasing the efficiency. Second, the highest-ranked applications tend to focus on three core areas of operations optimization (particularly through scenario testing), workforce enhancement (through training and automation), and safety improvement. This pattern indicates that Industry 4.0 adoption in maritime industries is driven by a balanced consideration of the operational efficiency, human factors, and risk management (Zarei & Naderi, 2024). Third, the relatively lower ranking of infrastructure technologies like IoT (4.83) and Cloud Computing (4.02) may indicate that these are increasingly viewed as fundamental enablers rather than strategic differentiators. This finding aligns with the technology adoption lifecycle model, where certain technologies transition from competitive advantages to necessary conditions for operation.

In examining the applications of Industry 4.0 technologies, Operations Optimization by Testing Different Scenarios ranked first. This finding is consistent with the results of Yang et al.'s (2018) study, which showed that simulation and optimization of processes before implementation can reduce design time by up to 50 percent. Additionally, Automatic Guidance of Vehicles in Port Area and Employee Training with Virtual Models ranked as the second and third. This prioritization shows that the maritime industry is moving toward the operation automation and the development of human resource skills.

Big Data Analytics with a weight of 9.67 was identified as the fourth most important technology, indicating the growing importance of data-driven decision-making in maritime industries. Among the applications of this technology, Data-Based Decision-Making with a final weight of 402.3687 ranked fourth, demonstrating the vital role of data analysis in optimizing the operations.

Cyber-security with a weight of 8.05 ranked fifth, indicating that with increased system connectivity and digitization of operations, the protection of vital infrastructure has become an important priority. Additionally, it was found that infrastructure technologies such as Internet of Things with a weight of 4.83 and Cloud Computing with a weight of 4.02 are in lower ranks, which could indicate the relative maturity of these technologies in industry.

Implementation Challenges of Industry 4.0 Technologies

While the prioritization of Industry 4.0 technologies offers a strategic guide for maritime industries, their implementation is not without challenges. High initial investment costs, often reaching hundreds of millions of dollars for technologies like Digital Twin Systems or port automation, pose significant financial barriers, particularly for smaller organizations (Vanelslander et al., 2019). Technical complexities, such as integrating new systems with legacy infrastructure, further complicate the adoption, requiring substantial expertise and time (Boyes et al., 2016). Regulatory constraints, including compliance with international maritime standards and environmental regulations, add another layer of difficulty, as organizations must navigate complex approval processes (Acciaro et al., 2018). Additionally, the increased connectivity inherent in technologies like IoT and Cloud Computing raises cyber-security risks, necessitating robust protection measures to safeguard critical infrastructure (Kim, 2017). Workforce training is also a critical barrier, as employees must acquire new skills to operate advanced systems, which can strain organizational resources (Chu et al., 2018). These challenges highlight the need for careful planning and resource allocation to ensure successful technology adoption. Addressing these barriers through phased implementation, public-private partnerships, or targeted training programs could facilitate smoother integration of Industry 4.0 technologies in maritime industries.

Case Examples Supporting Prioritization

To validate the prioritization of Industry 4.0 technologies, real-world applications at leading ports provide illustrative evidence. The Port of Rotterdam, a pioneer in Digital Twin Systems, implemented a digital twin for terminal operations, resulting in a reported 25% increase in the operational productivity by optimizing resource allocation and reducing vessel turnaround times (PTI, 2019). The initial investment was substantial, estimated at €50 million, but the long-term savings in operational costs justified the expenditure. Similarly, the Port of Singapore adopted Robotics and Automation for container handling, achieving a 20% reduction in loading and unloading times through using automated guided vehicles and smart cranes (Woo, 2018). While the upfront costs for automation infrastructure were high, the port reported a 15% decrease in labor costs and improved safety outcomes. These cases align with our findings, where Digital Twin Systems (weight: 20.02) and Robotics and Automation (weight: 16.11) ranked the highest, demonstrating their transformative potential. Although comprehensive cost-benefit analyses require detailed financial data beyond this study's scope, these examples underscore the practical value of prioritizing high-impact technologies in maritime industries.

Conclusion

A review of previous research shows that despite the existence of extensive studies in the field of Industry 4.0 and its applications in maritime industries, there has been a significant gap in prioritizing and selecting these technologies; therefore, this research study attempted to help fill this research gap by providing a systematic framework for evaluating and prioritizing Industry 4.0 technologies. Asarian et al. (2025) showed that strategic flexibility and alignment of information technology strategy with organizational goals play a key role in improving the business performance in dynamic and changing environments. This is particularly important in maritime industries that face numerous challenges in adapting to emerging technologies. The results of this study can help managers and decision-makers in maritime industries to select and implement appropriate technologies and provide guidance for optimal resource allocation and reduction of investment risks.

Recommendations for Organizations at Different Digital Maturity Levels

To maximize the benefits of Industry 4.0 technologies, maritime organizations should adopt strategies aligned with their level of digital maturity. For beginner organizations, which may lack advanced infrastructure, we recommend starting with foundational technologies like IoT for equipment monitoring or Cloud Computing for data sharing. These technologies require moderate investment and provide immediate operational insights, building a base for further digitalization (Yang et al., 2018). Intermediate organizations, with some digital capabilities, should focus on integrating high-impact technologies like Robotics and Automation for port operations or Big Data Analytics for decision-making. These organizations can leverage the existing systems to scale up efficiency while investing in workforce training to support adoption (Chu et al., 2018). Advanced organizations, already equipped with sophisticated systems, should prioritize cutting-edge technologies like Digital Twin Systems for scenario testing or Cyber-security to protect the integrated networks. These organizations can also lead industry-wide initiatives, such as developing shared digital platforms or piloting Blockchain for supply chain transparency (Li, 2018). Tailoring technology adoption to digital maturity ensures the optimal resource use and minimizes the implementation risks, enabling organizations to progressively enhance their competitiveness and sustainability.

Limitations and Future Research Directions

This study has several limitations that should be acknowledged. First, the research was conducted with a limited sample of experts from one country, which may affect the generalizability of the findings to other geographical contexts with different technological adoption rates and maritime industry characteristics. Second, the rapid pace of technological advancement means that new technologies may emerge and change the priority landscape in a relatively short time frame. While this study now includes a discussion of implementation challenges—such as financial, technical, regulatory, and human resource barriers—a comprehensive analysis of these factors was beyond its scope, leaving room for future studies to investigate overcoming these barriers through implementing approaches like case studies or cost-benefit analyses.

The study focused primarily on the prioritization of technologies without deeply exploring the implementation challenges, cost-benefit analysis, or the interdependencies between different technologies. The barriers to adoption, including financial constraints, regulatory issues, and workforce readiness, were not extensively examined. To address the organizational diversity, this study provides tailored recommendations for different digital maturity levels, though these are based on broad categorizations of beginner, intermediate, and advanced stages. Future research could refine these into more granular frameworks by considering specific contexts such as organization size, sector, or regional differences.

For future research, it is suggested to investigate the mutual impact of different technologies on each other and the role of contextual factors such as organization size, digital maturity, and organizational culture in the successful implementation of these technologies. Longitudinal studies tracking the implementation process and the outcomes of these technologies would provide valuable insights into their real-world effectiveness and challenges.

Further research could also explore the development of more detailed implementation roadmaps for maritime organizations at different stages of technological maturity, as well as conducting comparative analyses across different countries and maritime sectors. Finally, future studies should consider the sustainability implications of Industry 4.0 technologies in maritime industries, examining how these technologies can contribute to environmental goals while improving operational efficiency.

REFERENCES

Acciaro, M., Ferrari, C., Lam, J. S. L., Macario, R., Roumboutsos, A., Sys, C., Tei, A., & Vanelslander, T. (2018). Are the innovation processes in seaport terminal operations successful?, *Maritime Policy & Management, 45*(6), 787-802.

Asarian, M., Jami Pour, M., & Talafidaryani, M. (2025), "Recognizing the ideal patterns of strategic flexibility, IT strategy and business performance: a cluster analysis approach", *International Journal of Productivity and Performance Management*, *74* (3), 867-888. https://doi.org/10.1108/IJPPM-11-2023-0593.

Berns, S., Vonck, I., Dickson, R., & Dragt, J. (2017). Smart ports. Point of View. Deloitte Port Services.https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/energy-resources/deloitte-nl-er-port-services-smart-ports.pdf.

Boyes, H., Isbell, R., & Luck, A. (2016). Code of practice: cyber security for ports and port systems. *Department for Transport, London*.

Chu, F., Gailus, S., Liu, L., & Ni, L. (2018). The future of automated ports. McKinsey & Company. https://www.mckinsey.com/industries/travel-transport-and-logistics/our-insights/the-future-of-automated-ports

Fasanghari, M., & Asarian, M. (2024). Identifying and Prioritizing the Fifth-generation Wireless Mobile Communication (5G) Projects in Smart Tourism. *Journal of Knowledge Economy Studies, 1*(1), 71-91. https://doi.org/10.22034/kes.2024.2046023.1034.

Hafezniya, H., & Ansari, M. (2024). A systematic literature review of leadership styles for effective decision-making in the VUCA environment. *Journal of Business Management* (ahead-of-print). 10.22059/jibm.2024.371903.4747.

Harsha Vardhan, V. S., R. L., Aditya Reddy, K., & M. Mourya (2023). Mitigating counterfeiting using blockchain enabled product authentication. *International Journal for Research in Applied Science and Engineering Technology, 11*(4), 583-589.

Ilias, L., Tsapelas, G., Kapsalis, P., Michalakopoulos, V., Kormpakis, G., Mouzakitis, S., & Askounis, D. (2023). Leveraging extreme scale analytics, AI and digital twins for maritime digitalization: the VesselAI architecture. *Frontiers in Big Data*, *6*, 1220348.

Jardas, M., Dundović, C., Gulić, M., & Ivanić, K. (2018). The role of Internet of Things on the development of ports as a holder in the supply chain. *Journal of Maritime & Transportation Sciences, 54*(1), 71-73.

Jayavardhana, G., Rajkumar, B., Slaven, M., & Marimuthu, P. (2013). Internet of things (IoT): A vision, architectural elements, and future directions. *Future Generation Computer Systems, 29*(7), 1645-1660.

Kamolov, A., & Park, S. H. (2019). An IoT based smart berthing (parking) system for vessels and ports. In *Mobile and Wireless Technology 2018: International Conference on Mobile and Wireless Technology (ICMWT 2018)* (pp. 129-139). Springer Singapore.

Kim, J. H. (2017). A review of cyber-physical system research relevant to the emerging IT trends: Industry 4.0, IoT, big data, and cloud computing. *Journal of Industrial Integration and Management, 2*(3), 1750011.

Kosova, F., & Ünver, H. (2022). A digital twin framework for aircraft hydraulic systems failure detection using machine learning techniques. *Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, 237*(7), 1563-1580.

Krantz, M. (2017). Using secure IoT for efficient smart port operations. *Port Technology International Journal, 76*(4), 14-16. https://www.porttechnology.org/technical_papers/using_secure_iot_for_efficient_smart_port_operations.

Li, L. (2018). China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". *Technological Forecasting & Social Change, 135*, 66-74. https://doi.org/10.1016/j.techfore.2017.05.028.

Liu, X. (2023). A new perspective on digital twin-based mechanical design in industrial engineering. *Innovations in Applied Engineering and Technology*.

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration, 15*, 80-90.

Pérez-Lara, M., Saucedo-Martínez, J. A., Marmolejo-Saucedo, J. A., Salais-Fierro, T. E., & Vasant, P. (2020). Vertical and horizontal integration systems in Industry 4.0. *Wireless Networks*, *26*(7), 4767-4775.

PTI. (2019). How 'Digital Twins' are evolving ports. *Port Technology International Journal*. https://www.porttechnology.org/news/how_digital_twins_are_evolving_ports.

Rezaei, J. (2016). Best-worst multi-criteria decision-making method: Some properties and a linear model. *Omega, 64*, 126-130.

Rodič, B. (2017). Industry 4.0 and the new simulation modelling paradigm. *Organizacija, 50*(3), 193-207.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston consulting group*, *9*(1), 54-89.

Tang, L., et al. (2022). Digital supply chain transformation in Industry 4.0: A comprehensive framework. *International Journal of Production Economics, 245*, 108378.

Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., & Nee, A. (2018). Digital twin-driven product design framework. *International Journal of Production Research, 57*(12), 3935-3953.

Turgay, S., & Erdoğan, S. (2023). Enhancing trust in supply chain management with a blockchain approach. *Journal of Artificial Intelligence Practice, 6*(6), 56-64. https://doi.org/10.23977/jaip.2023.060609.

Vanelslander, T., Sys, C., Lam, J. S. L., Ferrari, C., Roumboutsos, A., Acciaro, M., Macário, R., & Giuliano, G. (2019). A serving innovation typology: Mapping port related innovations. *Transport Reviews, 39*(5), 611-629.

Wang, Y., Han, J. H., & Beynon-Davies, P. (2018). Understanding blockchain technology for future supply chains: A systematic literature review and research agenda. *Supply Chain Management: An International Journal, 24*(1), 62-84.

Woo, J. (2018). PSA Singapore unveils advanced port technologies in new exhibition. *The Business Times.* https://www.businesstimes.com.sg/transport/psa-singapore-unveils-advanced-port-technologies-in-new-exhibition.

Xisong, D., Gang, X., Yuantao, L., Xiujiang, G., & Yisheng, L. (2013, July). Intelligent ports based on Internet of Things. In *Proceedings of 2013 IEEE International Conference on Service Operations and Logistics, and Informatics* (pp. 292-296). IEEE.

Xiu, C., & Chen, K. (2021). Industry 4.0 and smart manufacturing: A key technology roadmap and implementation framework. *IEEE Access, 9*, 12345-12356.

Yang, Y., Zhong, M., Yao, H., Yu, F., Fu, X., & Postolache, O. (2018). Internet of things for smart ports: Technologies and challenges. *IEEE Instrumentation & Measurement Magazine*, *21*(1), 34-43.

Zarei, F., & Naderi, J. (2024). Industry 4.0 Technology Communication Models for Achieving Sustainable Supply Chain: A Roadmap and Impact Dimensions. *Journal of Knowledge Economy Studies (JKES), 1*(2), 193-220.

Zhang, C., & Chen, Y. (2020). A review of research relevant to the emerging industry trends: Industry 4.0, IoT, Block Chain, and Business Analytics. *Journal of Industrial Integration and Management, 5*(1), 165-180. https://doi.org/10.1142/S2424862219500192.