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ARTICLE

Digital Twins for the Sea: Building Resilient Intelligent Ship-Shore Remote Collaboration Systems

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ABSTRACT

As global maritime operations face increasing demands for safety, efficiency, and resilience, the need for intelligent, integrated solutions has never been more critical. Digital twins—virtual, data-driven replicas of physical ships—are emerging as transformative tools for enabling real-time monitoring, simulation, predictive analytics, and coordinated decision-making between shipboard systems and shore-based stakeholders. This paper explores the conceptual foundation and functional roles of digital twins within maritime contexts, emphasising their contribution to resilient ship-shore remote collaboration systems. With the help of the industry case studies and secondary data of companies like Rolls-Royce, Kongsberg Maritime, and the Port of Rotterdam, the paper can point out best practices and challenges behind the digital twin technology implementation. It says that digital twins are not only leading to the advancement of situational awareness and the reliability of operational reliability, but they are transforming the human-machine interface within the maritime ecosystem. The conclusion of the study presents some of the main enablers, policy-related considerations, and future scale-ups of digital twin adoption in global shipping.

1. Introduction

Maritime is one of the industries within which a comprehensive digital transformation is going on under the influence of the growing demands of operational efficiency, environmental sustainability, and safety. International trade continues to be largely dependent on global shipping, whereby more than 80 per cent of worldwide transportation of merchandise is done by this means of transport. Nevertheless, being a matter of such

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great importance, the pressure to become modernized in terms of operating the traditional maritime systems, which have already relied on manual controls, ineffective communication channels, and reactive decision-making, has been on the rise. Against this backdrop, there is increased demand than ever before to have smart, adaptable systems that can connect the ship and the shore. Technological innovation that is fronting this shift is the digital twin (DT), which refers to a continuously updated, virtual model of a physical asset that could facilitate real-time monitoring, simulation, and predictive analytics [1,2].

Digital Twin could be game-changing in the maritime environment in terms of ship-shore synergy. They are virtual versions of vessels in real life, and they mimic functioning characteristics and performance modes through constant data synchronisation. These twins offer shore-based crews with a clear overview of the situation on ships, as well as detailed information clarity on the situation on board so that informed decisions can be made on time without physical access. Being more than a simple data dashboard, a maritime digital twin is an intelligent platform learning not only from past data but also from real-time data, simulating the future state, and guiding the operation optimization in the full ship lifecycle. Whether it comes to the planning of navigation or scheduling maintenance and safety exercises, digital twins can unify the physical and digital aspects of the maritime operating environment with the human interface and result in an interactive system [3].

Traditionally, the issue of communication delay, lack of visibility into the processes onboard, and exposure to the risk of random events, including the failure of equipment or severe weather conditions, have been the major challenges of ship-shore collaboration. Furthermore, remote coordination was shown to have fundamental flaws during the COVID-19 pandemic, a problem that needs resilient digital infrastructures as soon as possible. Therefore, the maritime industry has started to implement digital twins to offer real-life operational resilience, real-time situational awareness, and enable real-time diagnostics. It is also complemented by the progress in sensor technology, cloud computing, Internet of Things (IoT), and artificial intelligence (AI), all of which form the foundation of the efficient digital twin's architecture.

Digital twins have more to offer than just efficiency or convenience; they are critical to developing ship-shore resilient systems of remote collaboration that are intelligent. In this sense, resilience means the ability of a system to foresee, sustain, cope with, and avert the impact of disruptive events. Based on past events, an intelligent system with DT will be able to learn and thus run simulation exercises to evaluate future risks and dynamically adjust resources or divert ships to avoid the crisis. Digital twins provide a proactive safety and efficiency solution with real-time alerts, predictive maintenance, and scenario testing to decrease downtime in operation and human error. In addition, they allow harmonious incorporation of shipboard and shore-based systems, which allows constant feedback and collaborative decision-making between the crewmembers, operators and maritime authorities [4,5].

In this research paper, the author will discuss the place of digital twins in the context of a stronger and more resilient cooperation between ships and shore-based stakeholders. In contrast to research that uses primary data (in the form of a survey or an onboard trial), a secondary data approach is applied in this paper, which is based on the systematic review of literature and working examples of digital twin practice in the maritime context. It explores the theoretical foundations of digital twins as socio-technical systems, their functional roles in simulation, monitoring, and prediction, and their practical implementations in maritime operations. The paper also discusses the challenges of deploying digital twins at scale, including issues of interoperability, cybersecurity, and human-system integration [6].

The structure of the paper is as follows: Section 2 develops a conceptual framework for understanding digital twins in the maritime environment, outlining their key components, data flows, and technological enablers. Section 3 explores the operational functions of digital twins in enhancing ship-shore collaboration, focusing on simulation, diagnostics, analytics, and resilience-building. Section 4 presents a set of global case studies that illustrate successful DT applications, drawing insights from companies and port authorities that are leading the way in digital transformation. Finally, Section 5 concludes by summarising the major findings, reflecting on the policy and industrial implications, and suggesting future research directions.

By emphasising the strategic role of digital twins in reshaping maritime operations, this paper contributes to a growing body of research on maritime digitalisation and cyber-physical systems. It also offers practical insights for ship operators, system developers, port authorities, and policymakers seeking to strengthen maritime resilience through intelligent, integrated technologies. As the maritime sector continues its digital evolution, digital twins stand out as a key enabler of smarter, safer, and more sustainable shipping [7,8].

2. Conceptual Framework: Digital Twins in Maritime Context

2.1 Understanding Digital Twins: Origins and Evolution

The concept of a Digital Twin (DT) originated in the aerospace and manufacturing industries, where engineers sought to replicate physical systems in virtual environments for analysis, testing, and optimisation. A digital twin is more than just a static model—it is a dynamic, data-driven representation of a physical asset or process that evolves through real-time data integration. According to the U.S. National Institute of Standards and Technology (NIST), a digital twin integrates "multi-physics, multi-scale, probabilistic simulations" and utilises real-time data to reflect the condition of its physical counterpart.

In the maritime domain, a digital twin typically mirrors the operational characteristics of a vessel, including propulsion systems, structural elements, navigation patterns, cargo conditions, and even crew behaviour. The goal is to create a closed-loop system where data continuously flows between the physical ship and its virtual model, enabling synchronised operation, real-time diagnostics, and predictive analytics [9].

2.2 Key Components of a Maritime Digital Twin

A maritime digital twin consists of several interconnected components that ensure the seamless replication of ship systems and processes:

- **Physical Vessel**: The ship itself, equipped with a wide array of sensors and data acquisition tools monitoring various systems (e.g., engines, hull, navigation, fuel systems).
- **Digital Model**: A computationally rich, interactive model that reflects the ship's structure and behaviour. This may include 3D visualisations, hydrodynamic models, and system schematics.
- **Data Infrastructure**: The backbone of the DT system, including edge devices, satellite/shore communication links, cloud computing platforms, and onboard servers. This infrastructure supports real-time data acquisition, processing, and visualisation.
- **Analytical Engine**: AI and machine learning algorithms that process incoming data, identify anomalies, predict failures, and suggest optimised decisions.
- **Human Interface Layer**: Dashboards and control panels accessed by shore-based operators and onboard crew, enabling interactive engagement with the digital twin.

This ecosystem enables **bidirectional communication**: ship sensors feed live data into the digital twin, while simulation outputs or predictive analytics from the digital model can inform operational adjustments in the real ship [10].

2.3 Theoretical Models Supporting Digital Twin Integration

To fully understand how digital twins function within ship-shore systems, it is important to ground the discussion in relevant theoretical perspectives:

- **Cyber-Physical Systems (CPS)**: Digital twins are a form of CPS, where physical and computational components are tightly integrated. In maritime applications, CPS involves embedded systems that gather sensor data and execute control operations, closing the loop between data collection and decision-making.
- **Socio-Technical Systems Theory**: Effective DT integration requires more than technical capabilities; it involves human operators, organisational workflows, and institutional norms. Ship-shore systems are socio-technical by nature, and DT adoption must account for training, trust, and governance structures.
- **Resilience Engineering**: The framework represents systems in their ability to predict, absorb, adapt to and recover from disruption. DTs facilitate resilience through continuous monitoring, predictive diagnostics, and reconfiguration at high velocity to address the changing risks by reducing the need to shut down operations (e.g., to deal with mechanical, cyber-attacks or environmental risks) [11].

3. Functional Roles of Digital Twins in Ship-Shore Operations

Digital twins (DTs) are not merely digital replicas; they are variously enabling in the maritime space things like simulation, monitoring, diagnostics, and decision-making. They are particularly important in resilience planning, real-time operations and predictive maintenance in enabling cooperation between ships and the shore. This is the description of the utility of digital twins in making ship-shore systems more intelligent and more adaptive, based on secondary sources and cases of major shipping companies.

3.1 Simulation, Scenario Testing

Digital twins are among the first and most prominent tools to use: simulation, e.g., it is possible to build a virtual version of a complicated ship system or a whole voyage and check it under safe and risk-free conditions.

- **Operational Scenarios:** DTs may allow operators to conduct what-if scenarios to represent different environments (e.g., different sea states) and parametric failures (e.g., engine failure) or evacuations. Such simulations allow assessing decisions without contributing to the vessel or the crew being at risk.
- **Training and Human Factors:** Digital twins could be used as a training tool that provides a realistic environment in which onboard crew members and the staff onshore could simulate actions like docking, route planning, or manipulation of machinery under diverse conditions. Veering towards the example of Scandinavian maritime academies, which have recently adopted DT-based simulators which also have the same configurations as the ships utilised in the fleet.
- **Design Optimisation:** DTs are applied by naval architects and engineers to perform the ship design and retrofitting. They can also do performance optimisation first via simulation of various hull designs or propulsion systems before the real thing.

DTs assist crews and managers in developing anticipatory knowledge because simulating a wide variety of operational and emergency conditions on the DT allows them to develop and maintain an awareness of those possibilities [12].

3.2 Real-Time Monitoring and Diagnostics

Digital twins play a critical role in monitoring the condition and detecting faults across the shipboard and shore-side systems on an ongoing basis.

- **Machinery Health Monitoring:** DTs can monitor data from sensors in engines, pumps, generators, and HVAC systems and determine wear and tear. Examining parameters of temperature, vibration, pressure and so on, the DT can find the aberrations that will suggest the cases of small-scale failures.
- **Structural Monitoring:** DTs attached to the hull and superstructure can alert the operator of fatigue, corrosion or deformation in real-time, particularly useful to ships in rough or icy water.
- **Navigation and Environmental Awareness:** DTs combine input of radar, GPS, Automatic Identification Systems (AIS) and weather satellites to keep an operating picture alive. An onshore mission can monitor the location, velocity and course of a ship and offer distant direction when required.

Real-time monitoring increases not only the respondent level of awareness but also enables the quick recovery of intervention in case there are any problems, hence decreasing downtimes and eliminating expensive fixes or accidents [13].

3.3 Predictive Analytics and Prescriptive Analytics

Digital twins can be an effective means of predictive maintenance and decision support as they gather operational data.

- **Failure Forecasting:** AI-driven systems within the model of DT have the capabilities of identifying patterns that precede system failure. Suppose part of a fuel pump is vibrating; it may be predicted, weeks ahead of time, by examining the rate at which the vibration of the fuel pump is getting worse, week on week.
- **Maintenance Optimisation:** Rather than applying a fixed-schedule maintenance schedule, DTs allow condition-based maintenance-maintaining the components only when they need it. This saves expenses and increases the life of the assets.

Prescriptive Decision Support: Advanced DTs not only predict what can happen but also propose actions as well. An example is that, in situations where rough seas are predicted, a DT can suggest optimal routing or modification of the ballast to help reduce the usage of fuel and allow greater safety.

- **Regulatory Compliance:** Emission and ballast water discharge monitoring provides DTs with real-time monitoring capability, thus notifying the crew of approaching regulatory limits. It will help in ensuring that they are in line with global policy, MARPOL, the IMO 2020 act and other similar environmental structures.

Digital twins can enhance the adoption of a proactive approach to safety culture and data-driven decision-making at all levels because of shifting reactive strategies to predictive and prescriptive ones [14,15].

3.4 Resilience and Risk Management

In maritime operations, resilience refers to the ability to respond effectively to disruptions—whether mechanical, environmental, or cyber-related. DTs contribute to resilience in several critical ways:

- **Redundancy and Backup Planning**: DTs enable the simulation of backup routes, alternative energy configurations, and emergency protocols. These virtual rehearsals allow operators to prepare for contingencies in advance.
- **Real-Time Risk Assessment**: DTs can calculate real-time risk scores based on current operating

conditions. For example, if a vessel is entering high-traffic waters with high engine load and poor visibility, the DT may trigger a high-risk alert to both ship and shore personnel.

- **Cybersecurity Testing**: DTs can serve as virtual sandboxes where new software updates, communication protocols, or cyber defences are tested before deployment. This helps detect vulnerabilities without risking live operations.
- **Post-Incident Learning**: After incidents occur, DT logs and simulations can be reviewed to reconstruct timelines and analyse human-system interactions. This supports learning and continuous improvement.

Through these functions, digital twins not only enhance operational robustness but also support organizational learning, a critical component of resilience in high-risk industries [16].

3.5 Enhancing Communication and Coordination

DT deployment changes ship-to-shore communication in terms of offering a place to share the information and interact.

- **Cooperative Dashboards:** DT can be made accessible to onboard staff and the operators on shore, thus helping both to be on the same page, as far as the vessel status and upcoming decisions are concerned.
- **Automated Alerts and Escalation:** The DT system can also resolve abnormal behaviour that has been detected, e.g. sudden loss of propulsion and can automatically alert the engineering team and escalate the problem to the regulating body in the case of necessity.
- **Coordinated port-vessel planning:** DTs can interface the ship systems with port management systems, enabling more coordination of the docking, cargo handling and turnaround time. This will form a more effective logistic chain and reduce down-time.

DTs enable a novel type of ship-shore cooperation based on situational intelligence instead of manual reporting by enhancing understanding of both timeliness, clarity, and relevancy of the information they use. Digital twins have diverse functional applications in ship-shore operations, and they cut across simulation and diagnostics, to predictive analytics, and operational risk management activities. The given functions are not independent of each other but rather interdependent, forming a smart ecosystem of operations in which digital twins can become both observers and advisors. DTs can help make maritime operations more resilient, safer, and more efficient by making it possible to share data in real-time, perform proactive maintenance, and continuous learning [17-19].

4. Case Studies and Best Practices

Although the theoretical and operational models of digital twins (DTs) provide the pretext regarding the insights on their prospects, the real essence of the technology can be best depicted by its practical uses. Some of the major maritime institutions and technology suppliers around the globe have started to incorporate DTs in their activities. These case studies emphasise some good practices, learning, and new standards in designing resilient and intelligent systems of ship-shore remote collaboration.

4.1 Case Study 1: Rolls-Royce – Intelligent Awareness and Remote Operations

Overview:

Rolls-Royce, with its Marine division (acquired by Kongsberg Maritime), has been a leader in both autonomous and smart ships. Among its major innovations was the Intelligent Awareness (IA) System, which serves as a type of digital twin in navigation and situational tracking.

Key Features:

- The IA system collects data from radar, LIDAR, GPS, and cameras, and processes it using AI for real-time navigation support.
- It integrates with a DT to simulate vessel manoeuvres in congested waters or poor visibility conditions.
- Data is fed to a shore-based remote operations centre, where human operators can supervise or intervene as necessary.

Relevance to Resilience:

- The DT supports real-time decision-making for both autonomous and manned ships.
- By simulating risks (e.g., collision paths or restricted visibility), the system enhances safety and allows for remote intervention.
- During trials in Norway, the IA system enabled safer coastal navigation, even in complex fjord environments.

Best Practice Insight

Combining AI-powered perception systems with a DT model enables shared situational awareness between ship and shore, reducing the risk of human error and enabling faster response to changing environmental conditions [20].

4.2 Case Study 2: Kongsberg Maritime – Vessel Insight and Ship Digital Twins

Overview:

Kongsberg's Vessel Insight is a data infrastructure platform designed to create digital twins of vessels by collecting, contextualising, and analysing real-time data from ship systems.

Key Features:

- Cloud-based platform that integrates with onboard sensors and control systems.
- Provides real-time performance analytics, including fuel consumption, emissions, engine status, and route optimisation.
- Supports predictive maintenance and regulatory reporting.

Relevance to Ship-Shore Collaboration:

- DT data is made available to shore-side stakeholders, including fleet managers and service providers.
- Vessel Insight is interoperable with third-party applications, enabling collaborative diagnostics and maintenance planning.
- Shore-side teams can monitor the ship's status in real-time, making remote decisions without interrupting operations.

Best Practice Insight

By offering a standardised, scalable platform, Kongsberg ensures consistent data quality and compatibility across different vessels, improving fleet-level decision-making and reducing communication barriers [21-24].

4.3 Case Study 3: Port of Rotterdam – Digital Twin Infrastructure for Smart Port-Vessel Synchronisation

Overview:

The Port of Rotterdam, Europe's largest seaport, has developed a port-wide digital twin as part of its "Smart Port" strategy, aiming to synchronise port and vessel operations more efficiently.

Key Features:

- DT models the entire port environment, including berths, docks, tides, weather, and ship traffic.
- Ships approaching the port connect to the DT system for coordinated berthing and cargo operations.
- Predictive analytics are used to avoid congestion and optimise turnaround times.

Relevance to Remote Ship-Shore Collaboration:

- Ships and port authorities share a common operational picture, enabling proactive docking, refuelling, and maintenance planning.
- Through remote access, vessel crews can receive updates on port conditions, reducing waiting time and emissions at anchor.
- The DT supports "Just-in-Time" arrivals, where vessels slow down during transit to avoid idle time at port [25-27].

Best Practice Insight

Digital twins that extend beyond the vessel—integrating port operations—enable a system-of-systems approach, enhancing both maritime logistics and environmental performance.

4.4 Comparative Analysis and Lessons Learned

Cross-Cutting Best Practices:

- **Standardisation** of data formats and protocols is essential for DTs to function across systems and geographies.
- **Cybersecurity** must be prioritised when remote monitoring and control are involved.
- **Human-system integration** (e.g., training for remote operators) is critical to trust and usability.
- **Modularity and scalability** allow DT platforms to adapt to different ship types and operational scales.

Dimension	Rolls-Royce	Kongsberg	Port of Rotterdam
Primary Focus	Navigation and autonomy	Performance analytics and maintenance	Port-vessel synchronization
Scope	Vessel-level	Vessel and fleet-level	Ecosystem-level (vessels + port)
Technologies Used	LIDAR, radar, AI, DT simulation	IoT, cloud, predictive analytics	GIS, DT, AI, port logistics
Impact on Ship-Shore Ops	Shared awareness for navigation	Collaborative diagnostics	Integrated logistics planning
Resilience Contribution	Enhanced safety in real-time	Predictive fault management	Delay reduction and emissions control

4.5 Implementation Challenges

While these case studies show promising outcomes, they also highlight common challenges in implementing digital twins at scale:

- **Legacy System Integration**: Many older vessels lack the sensor infrastructure or data interfaces to support DTs without costly retrofitting.
- **Data Governance**: Ownership, access rights, and privacy of vessel performance data must be negotiated, especially in multinational fleets.
- **Crew Readiness**: Digital transformation must be accompanied by crew training and change management to ensure smooth adoption.
- **Regulatory Frameworks**: Lack of standard regulation for DT certification and remote operations

can hinder broader adoption.

This collection of case studies shows that digital twins already bring measurable value to maritime navigation, performance tracking, and the coordination of logistics. DTs are revalorising integrated, intelligent ship-shore synchronisation, making possible autonomous navigation and simplifying entry and exit from the port. The best practices on these implementations highlight the need to have a scalable architecture, a human-centred design and interoperable systems. The pace of transformation has been on an upward trend as more stakeholders come to terms with the digital transformation, the instances provide a roadmap to the implementation of DTs that do more than just optimise operations but also improve resilience throughout the maritime system [28-30].

5. Conclusion and Future Directions

The shipping sector is at the cusp of its digitalisation, where the ability to transform digitally has become one of the necessities. The complexity of vessels and port systems has increased, which has necessitated real-time visibility, dynamic and intelligent coordination, and risk management. Digital twins (DTs) have, in this regard, become one of the disruptive technologies in helping to increase resilience and cooperation between offshore and onshore operations. This paper has discussed the conceptual basis, functional use and practical implementation of digital twins in the shipping industry. DTs, being dynamic and data-driven models, reflecting the behaviour and the conditions of the physical ones, can execute a variety of purposes: simulation, training, predictive maintenance, diagnostics over a distance. Above all, they provide a communications link between onboard systems and shore-based decision makers, allowing a common operating picture and providing quick, knowledgeable reaction to changing circumstances. This paper has established that digital twins have the potential to tremendously enhance the safety of navigation, business optimization, and coordination of logistics activities with case studies presented by Rolls-Royce, Kongsberg Maritime, and the Port of Rotterdam. These deployments exhibit best practices, such as a modular design, real-time data integration, AI analysis and models, and cloud-based teamwork platforms. They also emphasize the role of cybersecurity, standardization and human-oriented design in establishing successful implementation of DT systems. Although advances have been made, there are challenges. Integration of digital twins and legacy ship systems, bridging regulatory gaps, crew readiness and data ownership are some of the most important aspects that need to be further addressed. Nevertheless, the trend is apparent; digital twins will not only have supportive roles, but they will also become vital in the development of future-proofed maritime infrastructures.

The digital twins are emerging as one of the most critical solutions to defining resilient, intelligent, and adaptive ship-shore ecosystems with increased autonomy and sustainability that the industry strives to achieve. The ability to learn, foretell, and inform decision-making in a complicated setting places them at the heart of digitalization in maritime. In the future, it may be important to continue working on the refinement of the standards of DT, introduce cross-vessel interoperability, as well as incorporate new technologies such as blockchain and edge AI into their system to further increase functionality.

To summarize, digital twins are transforming our concept of how to approach maritime operations, no longer as a series of closed mechanical operations, but as a network of intelligent human, physical, and digital elements that operate in concert. This paradigm is the path toward a safer, more efficient, and more resilient maritime future.

References

[1] Falidouri M. Cybersecurity in maritime digital twins (Master's thesis, Πανεπιστήμιο Πειραιώς).

[2] Margaretha R, Syuzairi M, Mahadiansar M. Digital transformation in the maritime industry: Opportunities and challenges for Indonesia. Journal of Maritime Policy and Strategy. 2024 May 30;1(1):1-2.

[3] CORTÉS-MURCIA DL, GUERRERO WJ, MONTOYA-TORRES JR. game-changing technologies, and physical internet: A systematic meta-review of literature.

[4] da Conceicao VF. Designing for Safe Maritime Navigation. Studying Control Processes for Bridge Teams (Master's thesis, Chalmers Tekniska Hogskola (Sweden)).

[5] Madusanka NS, Fan Y, Yang S, Xiang X. Digital twin in the maritime domain: A review and emerging trends. Journal of Marine Science and Engineering. 2023 May 10;11(5):1021.

[6] Barth L, Schweiger L, Galeno G, Schaal N, Ehrat M. Value creation with digital twins: Application-oriented conceptual framework and case study. Applied Sciences. 2023 Mar 9;13(6):3511.

[7] Kaklis D, Varlamis I, Giannakopoulos G, Varelas TJ, Spyropoulos CD. Enabling digital twilns in the maritime sector through the lens of AI and industry 4.0. Internationa Journal of Information Management Data Insights. 2023 Nov 1;3(2):100178.

[8] Piras G, Agostinelli S, Muzi F. Digital twin framework for built environment: a review of key enablers. Energies. 2024 Jan 16;17(2):436.

[9] Li L, Aslam S, Wileman A, Perinpanayagam S. Digital twin in aerospace industry: A gentle introduction. IEEE Access. 2021 Dec 20;10:9543-62.

[10] Pang TY, Pelaez Restrepo JD, Cheng CT, Yasin A, Lim H, Miletic M. Developing a digital twin and digital thread framework for an 'Industry 4.0'Shipyard. Applied Sciences. 2021 Jan 25;11(3):1097.

[11] Giering JE, Dyck A. Maritime Digital Twin architecture: A concept for holistic Digital Twin application for shipbuilding and shipping. at-Automatisierungstechnik. 2021 Dec 20;69(12):1081-95.

[12] Mayer I. Digital twins for the real world. Tilburg University; 2022 Jun 17.

[13] Shaveko O. Maintenance of Autonomous Vessels (advantages and disadvantages) in comparison with Conventional Ships.

[14] Liu Z, Meyendorf N, Blasch E, Tsukada K, Liao M, Mrad N. The Role of Data Fusion in Predictive Maintenance Using Digital Twins. InHandbook of Nondestructive Evaluation 4.0 2025 Jan 16 (pp. 1-23). Cham: Springer Nature Switzerland.

[15] Van Dinter R, Tekinerdogan B, Catal C. Predictive maintenance using digital twins: A systematic literature review. Information and Software Technology. 2022 Nov 1;151:107008.

[16] Erstad, E. Operational training for enhanced maritime cyber resilience: Bridging safety and security through maritime education and training.

[17] Aslam S, Michaelides MP, Herodotou H. Internet of ships: A survey on architectures, emerging applications, and challenges. IEEE Internet of Things journal. 2020 May 8;7(10):9714-27.

[18] Katsoulakos T, Tsiochantari G, O'Donncha F, Kaklamanis E, Maccari A, Mucharski M. Shipping digital twin landscape. InState-of-the-Art Digital Twin Applications for Shipping Sector Decarbonization 2024 (pp. 1-25). IGI Global.

[19] Homayouni SM, Pinho de Sousa J, Moreira Marques C. Unlocking the potential of digital twins to achieve sustainability in seaports: the state of practice and future outlook. WMU Journal of Maritime Affairs. 2025 Mar;24(1):59-98.

[20] Mihai S, Yaqoob M, Hung DV, Davis W, Towakel P, Raza M, Karamanoglu M, Barn B, Shetve D, Prasad RV, Venkataraman H. Digital twins: A survey on enabling technologies, challenges, trends and future prospects. IEEE Communications Surveys & Tutorials. 2022 Sep 22;24(4):2255-91.

[21] Menges D, Rasheed A. Digital Twin for Autonomous Surface Vessels: Enabler for Safe Maritime Navigation. arXiv preprint arXiv:2411.03465. 2024 Nov 5.

[22] Heikkilä M, Saarni J, Saurama A. Innovation in smart ports: Future directions of digitalization in container ports. Journal of Marine Science and Engineering. 2022 Dec 6;10(12):1925.

[23] Mihai S, Yaqoob M, Hung DV, Davis W, Towakel P, Raza M, Karamanoglu M, Barn B, Shetve D, Prasad RV, Venkataraman H. Digital twins: A survey on enabling technologies, challenges, trends and future prospects. IEEE Communications Surveys & Tutorials. 2022 Sep 22;24(4):2255-91.

[24] Notteboom T. Dock labour and port-related employment in the European seaport system. ITTMA/University of Antwerp, Antwerpen. 2010.

[25] Farzadmehr M. AI-powered solutions assessment in port and maritime sector (Doctoral dissertation, University of Antwerp).

[26] Resende LM, Bilcati T, Pontes J, Betim LM. Assessing digitalization maturity in port environments: a comprehensive tool for logistics, operations, and planning management. Australian Journal of Maritime & Ocean Affairs. 2024 Dec 12:1-22.

[27] Donner M, Donner M, Kruk C. Supply chain security guide. Washington, DC, USA: World Bank; 2009 Jan.

[28] Juarez MG, Botti VJ, Giret AS. Digital twins: Review and challenges. Journal of Computing and Information Science in Engineering. 2021 Jun 1;21(3):030802.

[29] Rasheed A, San O, Kvamsdal T. Digital twin: Values, challenges and enablers from a modeling perspective. IEEE access. 2020 Jan 28;8:21980-2012.

[30] Mylonas G, Kalogeras A, Kalogeras G, Anagnostopoulos C, Alexakos C, Muñoz L. Digital twins from smart manufacturing to smart cities: A survey. Ieee Access. 2021 Oct 15;9:143222-49.