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Modeling and simulation methods used in the maritime industry: evolution, applications and future perspectives

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Abstract. Modeling and simulation (M&S) techniques have evolved from optional engineering tools to indispensable pillars of modern maritime practice. This article presents a comprehensive systematic review of the most important modeling and simulation methodologies applied to maritime industry processes, including workflows for ship design, shipyard fabrication and construction, port and terminal operations, vessel traffic management, maintenance scheduling, supply chain logistics, and risk management procedures. The study demonstrates that M&S techniques enable safer, more efficient, and more environmentally sustainable operations, validated by scientific standards.
The COVID-19 pandemic served as a critical catalyst, consolidating the strategic value of M&S as a central component of maritime resilience and innovation. This research traces the evolution of M&S adoption from 2010 to 2025, identifying four dominant research directions: maritime simulators, computational fluid dynamics (CFD)/finite element analysis (FEA), digital twins, and artificial intelligence-based methods. The analysis reveals that while traditional approaches dominated the 2010-2020 period, emerging technologies—particularly digital twins and AI-based methods—have accelerated exponentially since 2020, reflecting the maritime industry's accelerated digitalization. Forward projections through 2035 indicate that AI-based methodologies will experience the highest growth rate at approximately 329%, followed by digital twins at 147%, underscoring the fundamental transformation of maritime research and practice. The integration of these advanced modeling approaches offers optimal equilibrium between physical precision and computational efficiency for addressing complex maritime challenges.
Keywords: modeling and simulation, digital twins, artificial intelligence, maritime digitalization, maritime industry.

1. Introduction

Modeling and Simulation (M&S) techniques constitute tools utilized in various industries for over half a century, with increasingly significant outcomes, rendering them indispensable for the maritime sector. Over the past two decades, M&S techniques have experienced a rising trend in research and

development activities within this domain. The utilization of modeling and simulation tools has proven to be paramount for the advancement of the maritime industry, providing safer, more efficient, and ecologically sustainable operations that are scientifically validated (Partene et al., 2022). Given the highly intricate and ever-evolving nature of the maritime industry, characterized by stringent environmental regulations, persistent cost optimization competition, market responsiveness imperatives, and growing process automation trends, these modeling and simulation tools offer an efficient and innovative approach to cost and risk reduction (Zghyer et al., 2022).

Moreover, achieving optimal performance across the complex systems of the maritime industry, spanning from vessel design and safe operation to port logistics and environmental risk assessment, necessitates modern modeling and simulation methodologies that can forecast performance, streamline processes, and mitigate risks without extensive physical experiments or real-world testing reliance.

Models are depicted as "representations" of real-life scenarios, with simulation being an experiment conducted on a model. These tools enable researchers and practitioners to delve into the behavior of complex systems in controlled environments, fostering comprehension, planning, and optimization of dynamic systems across various industries, thereby facilitating strategic decision-making and fostering innovation (Gazihan, 2024).

An examination of industry research reveals that a pivotal moment when the maritime industry increasingly turned to M&S techniques was during the COVID-19 pandemic, which posed unprecedented challenges to the maritime supply chain and impacted numerous aspects of global maritime operations (Partene et al., 2023, A). This period presented critical challenges ranging from the continuity of maritime personnel training and education activities, crew rotation difficulties, hindrances in maritime transportation processes across regions, to alterations in terminal operations due to mandated social distancing measures (Zghyer et al., 2022). This shift underscored the strategic value of M&S as a central component of maritime resilience and innovation.

Global seaborne transport continues to serve as the critical lifeline of international commerce amidst ongoing geopolitical volatility. According to the United Nations Conference on Trade and Development (UNCTAD, 2025), global seaborne trade volume expanded by 2.2% to reach 12.72 billion tons in 2024, while distance-adjusted trade (ton-miles) surged by 5.9% to a record 66.78 trillion ton-miles as vessel rerouting altered traditional shipping corridors. The maritime sector faces increasing pressures related to regulatory compliance, environmental sustainability, operational complexity, and cost optimization. Consequently, the adoption of advanced simulation, modeling, and digital transformation technologies has become crucial for maintaining competitiveness and achieving operational excellence (Iheanacho et al., 2025). The analysis conducted in this study aims to examine specialized studies and industry websites to assess the current state of applications and software tools utilized in the maritime industry to enhance processes, optimize performance, and drive innovation.

Current research identifies a wide range of applicable methods for maritime processes, including Discrete Event Simulation (DES) for port terminal optimization, Agent-Based Simulation (ABS) for maritime traffic, and System Dynamics (SD) for long-term strategic analysis. Advances in computing power and the emergence of Industry 4.0 technologies have facilitated the development of sophisticated approaches such as Digital Twins, integrating real-time data from IoT sensors to create faithful virtual replicas of physical systems.

The digital transition in the maritime sector signifies a fundamental shift from experience-based operational practices to data-driven decision frameworks and high-fidelity simulations. This transformation is supported by specialized software solutions, ranging from naval architecture platforms like MaxSurf or NAPA to complex port logistics flow simulation environments like FlexSim or AnyLogic.

The premise of our investigation posits that the methodical incorporation of emerging simulation methodologies, such as Digital Twins and Artificial Intelligence (AI), signifies more than just technological advancement. It signifies a fundamental shift in approach necessary to attain decarbonization and economic efficacy goals amidst escalating global uncertainties.

This research aims to analyze the contributions of these methods and software tools in optimizing processes within the maritime industry. The study objectives involve examining and highlighting the most common modeling and simulation methods used across all branches of the maritime industry for a comprehensive understanding of the field and to identify future research directions. Thus, modeling and simulation emerge as central components of maritime resilience and innovation, preparing the industry for a future characterized by sustainability and digital integration.

The research is structured as follows: the *introduction* chapter sets forth the strategic context and study objectives, the *research methodology* elaborates on the methods of collecting and systematically analyzing specialized literature, the *research* section scrutinizes modeling methodologies and software tools applicable to maritime processes, the *results and limitations* section synthesizes the impact of digital transformation and technological forecasts, and the *conclusions and future research directions* provide a synthesis of the findings and identify new research opportunities.

2. Research methodology

The research methodology employed in this study is grounded in systematic analysis of specialized literature and comparative synthesis to provide a comprehensive overview of the digital transition in the maritime sector, shifting from experience-based practices to data-driven decisions and high-fidelity simulations. Data collection involved querying five primary scientific databases: Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar. The search strategy targeted peer-reviewed publications using Boolean query strings combining keywords such as (*'maritime simulation'* or *'naval architecture software*') and ('*digital twin'* or *'artificial intelligence*' or '*CFD*' or '*FEM*'). A total of 374 studies were identified, from which 112 highly relevant papers were selected after applying eligibility criteria (english language, peer-reviewed status, direct maritime application, published between 2010 and 2025). The *Connected Papers* mapping platform was utilized to visualize bibliometric networks and citation linkages. Additionally, 45 specialized software profiling platforms were analyzed to construct an integrated overview of commercial and open-source simulation tools.

The analysis focused on the evolution of Modeling and Simulation (M&S) techniques from the period of 2010 to 2025, with emphasis on peak adoption dynamics during 2015–2025, utilizing 2025 as a reference milestone for the current state of technology. To provide insight into the future of the industry, the research includes an exploratory scenario-based forecasting component for the 2026–2035 period, which involves estimating potential growth rates in the number of publications by extrapolating the compound annual growth rate (CAGR) based on historical data from 2010–2025.

3. Research

3.1. The main modeling and simulation methods used in the maritime industry

According to specialized scientific literature published over the past 15 years, a total of 14 modeling and simulation methods have been identified within the maritime industry. These methods have been applied and refined over time to enhance research within the maritime field, as outlined in the table provided below.

Table 1. Comparative table of all modeling and simulation methods used in the maritime industry

Method	Modeling purpose	Required data type	Advantages	Limitations	Maritime applications
1. Discrete Event Simulation (DES)	Modeling operational processes	Arrival time, processing times, capacities	Highly accurate for flows; excellent for ports	Does not capture emergent behaviors	Terminals, shipyards, logistics
2. Agent-Based Simulation (ABS)	Modeling the behavior of autonomous entities	Behavioral rules, AIS, interactions	Captures emergence; ideal for traffic	High complexity	Navigation, traffic, autonomous systems
3. System	Analysis of	Aggregated	Excellent for	Does not model	Logistics

Method	Modeling purpose	Required data type	Advantages	Limitations	Maritime applications
Dynamics (SD)	feedback loops and long-term developments	data, flows, policies	strategic scenarios	operational details	chains, port policies
4. Monte Carlo Simulation	Modeling uncertainty	Probability distributions	Simple, robust, ideal for risk	Does not model dynamic processes	Collision risk, delays, weather
5. Hybrid Simulation (DES+ABS+SD)	Integration of multiple paradigms	Combination of operational and strategic data	Most realistic approach	High implementation cost	Smart ports, supply chain
6. SimOpt – Simulation + Optimization	Finding the optimal solution under uncertainty	Operational parameters, constraints	Ideal for planning	Requires computational resources	Berths, cranes, ship routing
7. Digital Twins	Real-time digital representation	IoT data, sensors, telemetry	Predictive, continuously updated	High cost, requires infrastructure	Autonomous ships, smart ports
8. Simulation enhanced with Machine Learning (ML)	Accelerating simulation through the use of AI (artificial intelligence)	Large historical datasets	Very fast, scalable	Requires large amounts of clean data	Fast CFD, congestion, consumption
9. Maritime Traffic Simulation (AIS)	Modeling real traffic	AIS, routes, speeds	Highly realistic	Depends on AIS quality	VTS, routing, emissions
10. CFD – Computational Fluid Dynamics	Modeling fluid flows	Geometry, boundary conditions	Extremely accurate	High computational cost	Hulls, propulsion, ports
11. FEM – Finite Element Method	Structural analysis	Material properties, loads	High structural accuracy	Requires complex meshing	Ships, platforms, pipelines
12. FVM – Finite Volume Method	Mass/energy conservation	Fluid parameters, initial conditions	Standard in CFD	High computational cost	Engines, ballast, pollution
13. MBD – Multi-Body Dynamics	Motion of rigid/flexible bodies	Mechanical, hydrodynamic parameters	Ideal for maneuvering	Requires hydrodynamic models	Cranes, anchoring, maneuverability
14. Oceanographic / Environmental Simulation	Modeling the marine environment	Meteorological-oceanographic data oceanografice	Essential for offshore	High complexity	Waves, currents, pollution

Recent advancements in computational power and Industry 4.0 technologies have enabled the development and implementation of sophisticated modeling and simulation approaches in the maritime industry, previously computationally prohibitive. Future modeling and simulation approaches will be more constrained, amalgamating multiple methods, becoming the predominant strategy, striking an optimal balance between physical accuracy and computational efficiency. (Mao et al., 2023).

A systematic literature review will highlight the current state of the art in the field, emphasizing the most significant methods for modeling and simulating processes within the maritime industry. This

comprehensive analysis examines modeling and simulation methods specifically applied to maritime industry processes, including ship design workflows, manufacturing and construction processes, port and terminal operations, ship traffic management, maintenance scheduling, supply chain logistics, and risk management procedures for classification purposes.

Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) - which applies the numerical Finite Element Method (FEM) - represent distinct physics domains. While CFD addresses hydrodynamic flow, resistance, and propulsion, FEM/FEA focuses on structural integrity and dynamic loading. In modern naval architecture, these complementary techniques are increasingly coupled through Fluid-Structure Interaction (FSI) solvers rather than acting as a single unified method.

Emerging literature supports the hypothesis that multi-method hybrid simulation (e.g., integrating DES, ABS, and System Dynamics) will become a key strategic direction for modeling complex systems. However, hybrid integration should be selective: while multi-paradigm approaches offer demonstrable benefits for large-scale logistics and automated port terminals, standalone methods remain preferable for single-domain engineering tasks to prevent unnecessary model complexity and computational overhead.

Discrete Event Simulation (DES) for maritime processes

Discrete event simulation is widely utilized in modeling maritime processes, particularly those involving queuing systems, resource allocation, and scheduling (Rosca et al., 2025). Within these models, system state changes occur only at discrete time points, coinciding with specific events such as ship arrivals at ports, container handling by cranes, or completion of maintenance tasks (Zhou et al., 2020). This method is particularly suitable for analyzing port operations, where vessels, docks, cranes, and terminal equipment interact in intricate ways. Employing DES to model equipment reliability in container terminals has proven valuable for assessing the propagation of component failures within maritime systems. By simulating failure rates of critical handling equipment like quay cranes and integrating repair time distributions, DES models can forecast system-level impacts on terminal throughput and pinpoint optimal maintenance strategies (Partene et al., 2026).

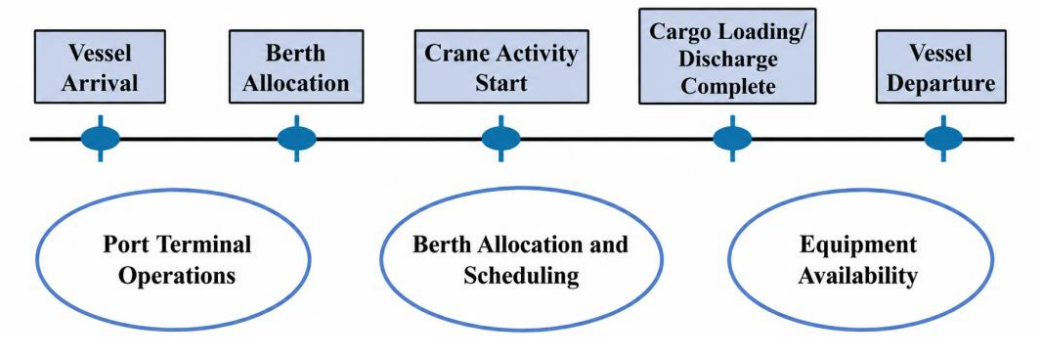


Figure 1. Example of a discrete event timeline representation model for a container terminal – source authors.

Optimization and mathematical programming methods and agent-based modeling for maritime systems

Mathematical optimization methods are crucial in supporting decision-making processes for various maritime operations, ranging from fleet management to route planning (Can, 2025). Linear programming (LP) has been widely employed in fleet allocation problems to determine the optimal number of each type of vessel serving different routes to minimize costs while meeting demand (Zhou et al., 2020). Network optimization using graph theory facilitates efficient resolution of routing and scheduling issues for vessels (Can, 2025). The hub-and-spoke network structure, prevalent in container shipping, can be optimized to minimize overall transportation costs while ensuring adequate

service frequency at each port (Zhang et al., 2025). Recent advances in multi-objective optimization enable simultaneous consideration of costs, transit times, and emissions, aiding in decision-making that balances economic and environmental objectives (Eom et al., 2023). Agent-based modeling (ABM) offers a bottom-up approach for simulating maritime processes by representing individual entities (vessels, ports, companies) as autonomous agents interacting according to defined rules (Li et al., 2024). ABM is particularly powerful for analyzing emergent behaviors resulting from local interactions, which are challenging to predict solely through top-down analysis (Zhou et al., 2020). Simulating maritime traffic using ABM can capture how individual navigation decisions of vessels collectively generate traffic patterns, congestion, and collision risks in narrow waterways (Partene et al., 2023, B).

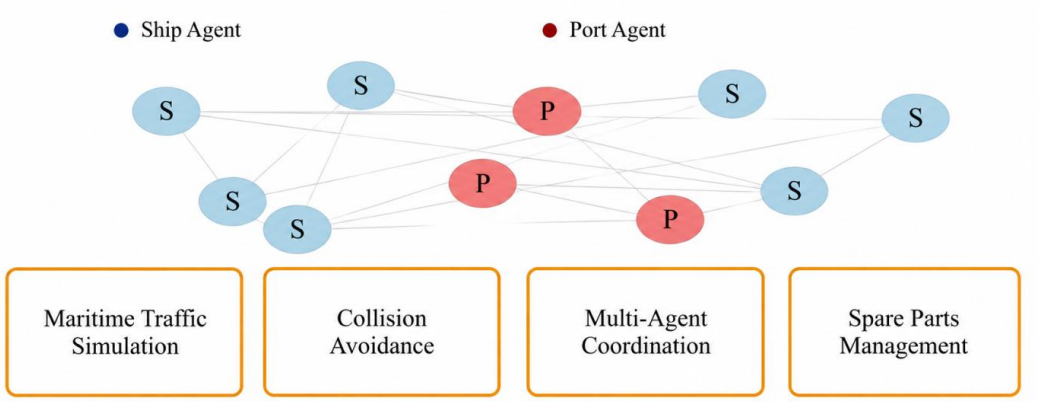


Figure 2. Example of agent-based modeling, autonomous agents that interact according to local decision-making rules – source authors

The importance of engineering process modeling for meeting ship design requirements

The shipbuilding industry has been scrutinized utilizing system dynamics to comprehend the boom-bust cycles (peaks and troughs in the global economy) driven by the feedback loop among ship demand, order backlogs, delivery delays, and capacity expansions (Stani et al., 2018). These models unveil how individual rational decisions by shipowners and shipyards can collectively result in overcapacity and financial distress industry-wide (Stani et al., 2018). Testing policies using system dynamics allows for assessing how various regulatory or market interventions could stabilize the industry's dynamics (Jiang et al., 2024).

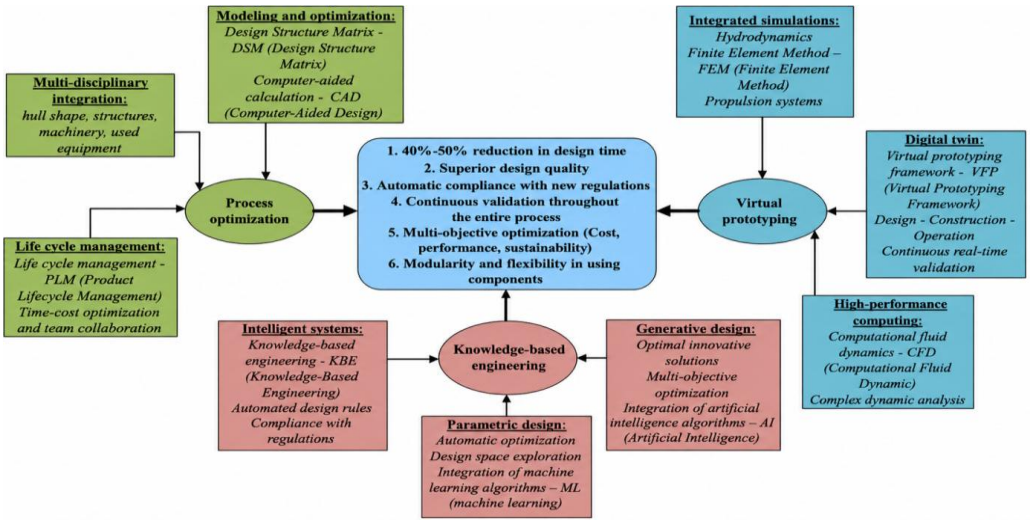


Figure 3. The results of the integrated ship design and engineering process by approaching three directions: process optimization - virtual prototyping and knowledge-based engineering - authors

Another crucial aspect integral to modeling and simulating maritime industry processes is the continuous optimization of ship design processes to meet operational, environmental requirements, as well as advancements in hull form and structural developments. Modeling these workflow processes entails interdisciplinary study implications to identify bottlenecks, optimize task sequences, refine design time, and total cost accuracy (Tadros et al., 2023).

Integrated ship design calculations situations combine computer-aided design (CAD) modeling, performance simulation, and decision support tools in unified workflows (Fonseca et al., 2023). Surrogate modeling using neural networks trained on simulation results accelerates this process significantly, enabling real-time exploration of the design space (Zhang et al., 2023).

Modeling processes regarding the design and construction of ships in shipyards, part of the maritime industry

To maintain continuous development and competitiveness in the maritime industry, shipyards must innovate to keep pace with industry changes and process acceleration by delivering intelligent ships (Hassani et al., 2016). This innovation aims to reduce environmental impact and operational costs through digital advancements. Shipyards need to align with Industry 4.0 tools and concepts to address complex issues, interconnected tasks, limited resources, and tight deadlines effectively.

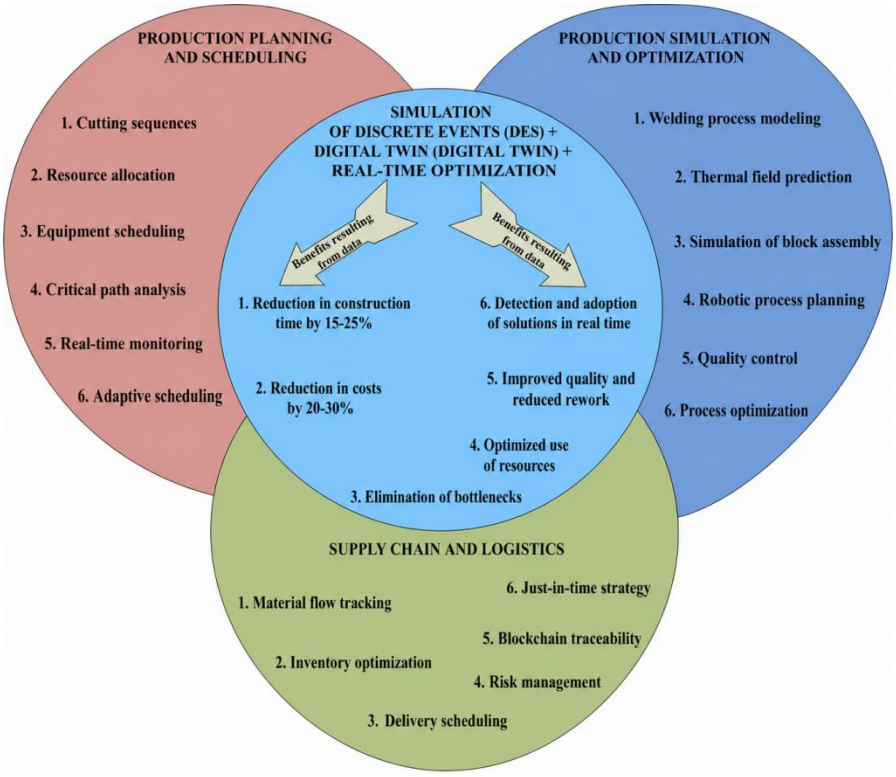


Figure 4. Key benefits and results obtained by applying modeling and simulation methods to shipbuilding and production processes in shipyards - source authors

The utilization of discrete event simulation in naval shipyards enables a detailed analysis of production flow, resource utilization, and throughput (Rosca et al., 2025). Process optimization in shipyards through simulation can determine the optimal allocation of resources to maximize productivity. It also facilitates tracking the entire shipbuilding process, revealing bottlenecks and improvement opportunities (Stani et al., 2018).

Simulation utilizing digital twin representations in naval shipyards accumulates performance data over time, enhancing planning accuracy and early identification of potential issues with predictability (Zhou et al., 2024). Manufacturing process simulation and optimization involve modeling welding processes, simulating assembly of large ship sections, and robotized ship construction planning (Nurcholis et al., 2024). These aspects enable specific sequence planning to determine optimal courses of action and identify assembly issues for part adjustment before physical construction commences, reducing rework costs.

Furthermore, shipyards need to carefully model supply and logistics chains to mitigate risks associated with global supplier networks and potential delivery delays, ensuring smooth operation by maintaining inventory levels with suitable strategies while upholding yard reliability (Li et al., 2024).

Modeling, simulation and optimization of port and terminal operations

Container terminal operations are extensively analyzed through modern modeling and simulation methods due to the intricate interactions among vessels, berths, quay or yard cranes, yard equipment, and internal or external transport trucks concerning terminal yard organization (Partene et al., 2026). The processes within these terminals necessitate continuous monitoring and meticulous optimization from a command center as any issue could trigger a cascading effect throughout the terminal workflow, potentially leading to a complete halt in operations. The allocation problem of berths, crucial for a terminal, influences when and where vessels should dock to minimize waiting times and maximize berth utilization (Eom et al., 2023). Simulation models are devised to optimize crane allocation decisions for each arriving vessel based on specific loading/unloading plans, aiming to reduce vessel operation time and maintain terminal efficiency.

Optimizing storage processes within the terminal yard addresses finding the most suitable location for container storage based on segregation criteria that can adapt to changing circumstances. This approach ensures direct subsequent container handling without unnecessary movements, consistently reducing truck waiting times (Partene et al., 2024). These models must adhere to terminal objectives and avoid conflicts, such as storing containers closest to the berth for quicker handling versus storage based on destination to prevent re-handling (Zeneli et al., 2024). Strategic storage decisions in the terminal yard evolve continuously as vessel schedules and container quantities are updated, accompanied by relevant information.

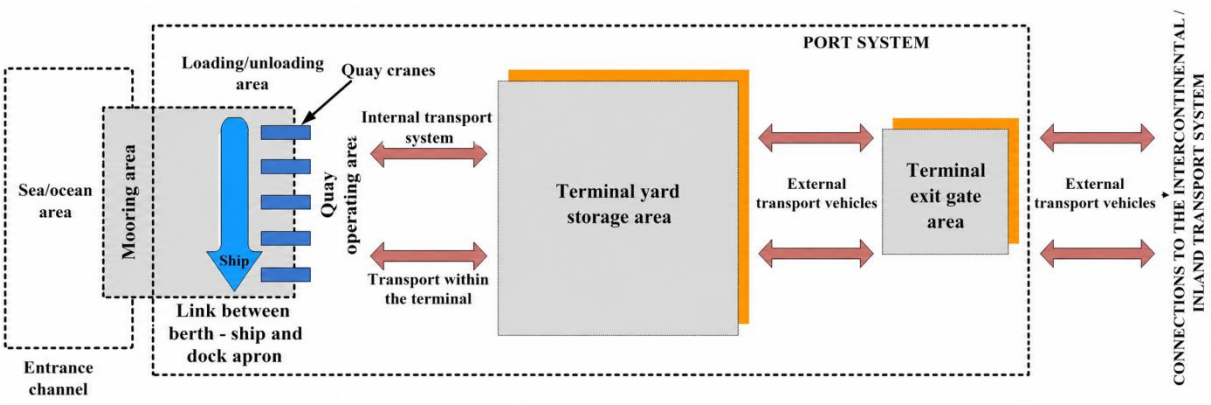


Figure 5. System layout of a conventional container port with the main subsystems – source authors

Modeling the operation and navigation process of ships in the maritime industry

Route optimization from a meteorological analysis perspective involves determining the vessel's route and speed regime to minimize fuel consumption, voyage time, or a combination of both while ensuring the safety of the crew, vessel, and cargo. These models incorporate weather forecasts for wind, waves, and currents, along with ship performance models predicting fuel consumption and speed loss in varying sea conditions (Pratil et al., 2021).

Dynamic route optimization involves real-time route updates during the voyage based on refined weather forecasts and actual field conditions. Meteorological routing services offer commercial implementation of these optimization models, typically reporting fuel savings of 3-8% compared to orthodromic routes (Pratil et al., 2021). Integrating digital twins allows real-time comparison of predicted performance with actual, continuously enhancing the accuracy of ship performance models and weather impact predictions.

Compliance optimization with Emission Control Areas (ECA) addresses additional route complexity and fuel selection when operating in regions with strict emission regulations (Vidovi et al., 2023). These models determine optimal routes that can deviate to minimize time in ECA zones, optimal speeds inside and outside ECAs, and optimal fuel switchover strategies to minimize total operating costs while ensuring compliance (Song, 2021). Uncertainty in regulations enforcement and fuel price volatility add stochastic elements requiring robust optimization approaches.

Designing containerized maritime transport networks determines which ports to include in each service route, types of vessels to deploy, and service frequencies to meet cargo demand while minimizing costs (Zhou et al., 2020). These large-scale optimization problems involve integer programming formulations with thousands of decision variables and constraints (Song, 2021). Hub-and-spoke network structures are common in liner shipping, requiring models that simultaneously optimize hub locations, feeder connections, and main routes.

Fleet deployment models allocate available vessels on different routes considering vessel capacities, speeds, fuel consumption rates, and charter costs (Zhou et al., 2020). These models address the trade-off between deploying larger, more fuel-efficient vessels on fewer routes versus smaller, more flexible vessels on multiple routes. Seasonal demand variations and uncertainty necessitate stochastic or robust optimization approaches to ensure solutions perform well in different scenarios (Hiekata et al., 2020).

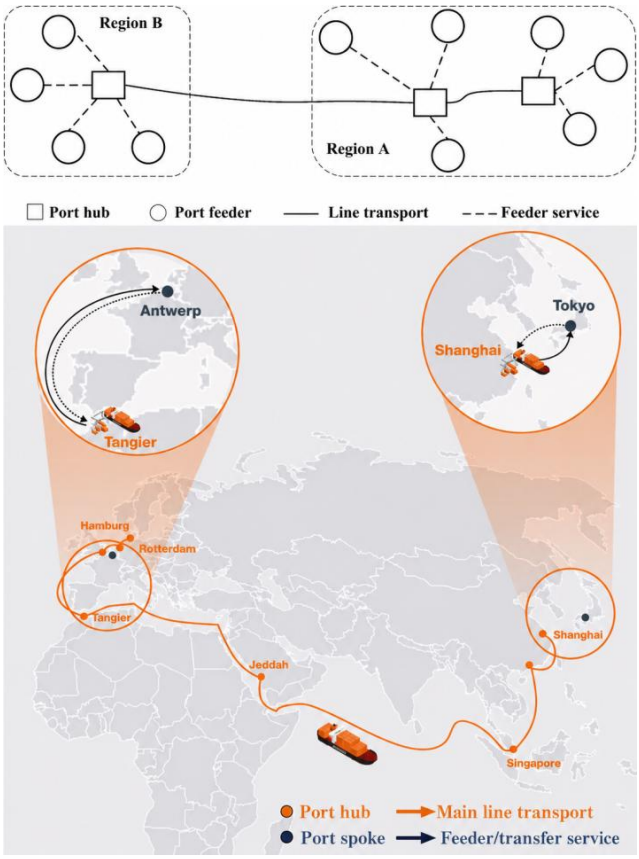


Figure 6. Network and example of hub-and-spoke container transport (authors using Hapag-Lloyd, 2024)

3.2. Analysis of the trend in recent years regarding the use of modeling and simulation techniques in the maritime industry

In order to comprehend the significance and evolution of Modeling and Simulation (M&S) techniques, a specialized literature review was conducted concerning scholarly works published in this field. The study period pertains to the utilization of M&S techniques over the past 15 years, with the reference milestone set at the year 2025. The most scrutinized scenarios involving modeling and simulation techniques that have significantly contributed to the advancement of the maritime industry in the last 15 years can be categorized into four main directions, namely: the utilization of simulators for various industry scenarios such as navigation command, communications, engine control room, safe cargo handling operations specific to multiple types of terminals, etc.; the use of Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) methods by industry engineers to design an efficient and structurally secure vessel for optimal water displacement and structural loading; the employment of digital twins to replicate real situations based on engineering principles and mathematical models, incorporating real data to subject the system to specific scenarios for analysis; and M&S methods centered on artificial intelligence usage, increasingly prevalent in the study of digitalization advancement in the maritime industry.

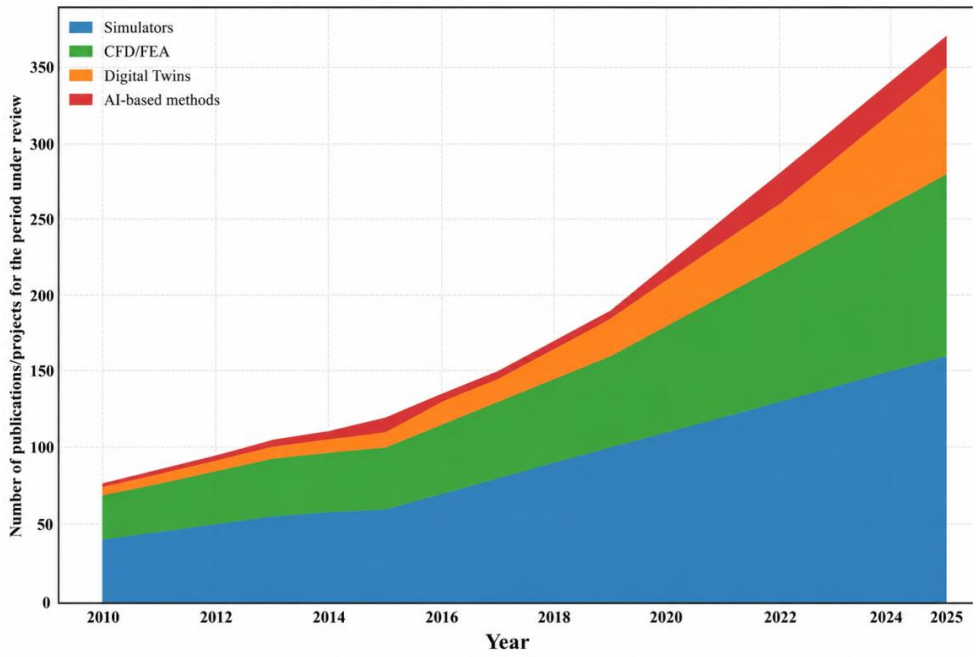


Figure 7. Evolution of research in the maritime industry using modeling and simulation methods for the period 2010 – 2025. Authors' research using information provided by Connected Papers Platform

The analysis of each situation in accordance with Figure 7 results in the following:

1. Research in the field of maritime industry simulators has steadily increased from around 40 publications in 2010 to approximately 160 publications in 2025;
2. CFD/FEA M&S methods have also evolved consistently from about 30 publications in 2010 to around 120 publications in 2025, becoming a standard in ship design;
3. Digital twin methods timidly emerged with about 5 publications in 2010, continuing this timid trend until 2020, when they began to trend upwards, accelerating the use of this method in specialized literature, leading to the publication of approximately 70 research papers in 2025;
4. Scientific works in the naval industry field with a methodology based on the use of artificial intelligence integration methods were marginal with approximately 2 publications in 2010, but gradually increased especially after 2020, reaching around 20 publications by 2025.

If we analyze the key method used in this analyzed period, the dominant periods are divided

according to table 2.

Table 2. Breakdown by period of key dominant M&S methods used for research in the maritime industry during 2010 - 2025

Time Interval	Key M&S Method	Usage Trends in the Maritime Industry	Remarks
2010 - 2017	***Maritime Simulators***	Approximately 30% of training institutions used simulators to train trainees in full and complex scenarios	The use of this method during this period focused on improving navigation safety
2018 - 2020	***CFD/FEA Method***	It became a standard in ship design workflows	Used for hull optimization, propulsion efficiency, and structural fatigue analysis, they improved collision probability and traffic flow prediction
2019 – 2021	***Hybrid Risk Analysis Models***	The combination of Monte Carlo simulations with hydrodynamic simulations was introduced	Collision probability and traffic flow prediction were improved
2020 – 2022	***Digital Twins Method***	The adoption of this method increased by 25% annually	It was primarily applied in predictive maintenance, smart shipping, and offshore energy systems.
2023- 2025	***AI-based Methods***	Generative artificial intelligence and case-based learning were integrated	Used for vessel traffic forecasting, optimization of processes in maritime terminals, autonomous navigation, and rapid validation of a new design.

3.3. Analysis of the forecasted trend regarding the use of modeling and simulation techniques in the maritime industry

From 2026 onwards, the trend of using modeling techniques for research in the maritime industry continues to rise, with the total number of publications across the four fields doubling by 2035 compared to the 2025 baseline.

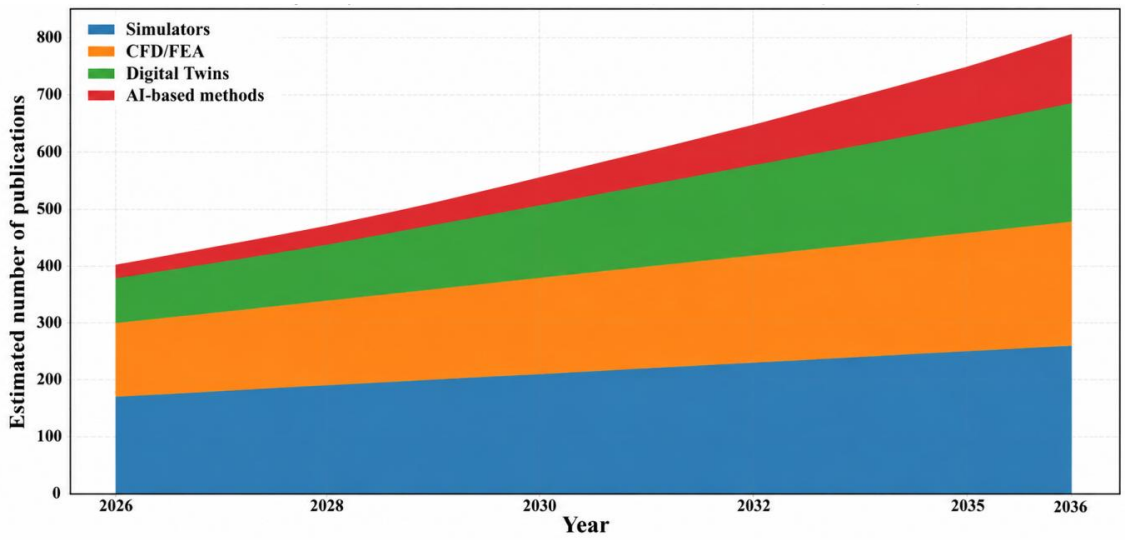


Figure 8. Forecast the evolution of research in the maritime industry using modeling and simulation methods for the period 2026 – 2035.

The forecast in Figure 8 is developed by the authors following a review of the literature, reports from databases evaluating recent studies in the field, industrial reports, and trend analyses (Serani et al., 2024; Wang et al., 2024; Dimitrios et al., 2023; Zeneli et al., 2024; and Guedes et al., 2024).

The analysis indicates that the four main directions will have the following forecast:

1. Maritime simulators will continue to play a central role in training personnel across various maritime industry sectors, maintaining dominance, with research publications based on this development method reaching approximately 260 by 2035.
2. M&S CFD/FEA methods will continue to demonstrate their importance in ship design and structural analysis, steadily increasing to about 220 publications by 2035. By 2030, most shipyards and other industry institutions are expected to adopt them as the standard for ship design.
3. The Digital Twins method will rapidly expand in the field, surpassing 210 publications by 2035, particularly crucial for predictive maintenance and intelligent transportation.
4. AI-based methods are projected to have the fastest growth rate, rising from around 28 publications in 2026 to about 120 by 2035, showcasing an increasing integration of automated learning and generative artificial intelligence in maritime research.

For a comprehensive overview of the growth rate by 2035 of the four main modeling and simulation methods for maritime research development, the key data will be detailed in Table 3.

Table 3. Growth rates for the most widely used M&S methods used in naval industry research with forecast for 2035

Method Used	**Number of research-oriented publications in 2026 - estimated**	**Number of research-oriented publications in 2035 - estimated**	**Growth Rate**
Maritime Simulators	~175	~265	**+51%**
CFD/FEA Methods	~130	~225	**+73%**
Digital Twins (Digital Twins)	~85	~210	**+147%**
Method based on the use of artificial intelligence	~28	~120	**+329%**

Table 3 illustrates the increasing adoption of various methods to contribute to the advancement of maritime research. Based on forecasts concerning digitalization initiatives, the development of autonomous vessels, IMO legislation regarding environmental regulations, shipyard modernization, and equipment lifecycle management in the maritime industry (Zhang et al., 2024), it is evident that digital twin methods and artificial intelligence utilization are projected to see significant growth rates surpassing traditional approaches, potentially leading to a convergence (Kim et al., 2025).

The numerical projections calculated for the 2026–2035 decade (+329% for AI-driven methodologies and +147% for Digital Twins) represent exploratory baseline scenarios derived from 2010–2025 historical CAGR trends. These scenarios reflect sustained growth momentum under baseline research adoption assumptions, rather than deterministic predictive forecasts.

3.4. Aspects regarding the need to transition from traditional operational practices to the use of simulation software

The maritime industry is facing increasing pressures related to compliance with regulations, environmental sustainability, operational complexity, and the need for cost optimization. Therefore, the adoption of advanced simulation, modeling, and digital transformation technologies has become essential for enhancing competitiveness and achieving operational excellence. This comprehensive analysis aims to review specialized studies and industry-specific websites to assess the current status of software applications and tools utilized in the maritime sector to improve processes, optimize performance, and foster innovation.

The digital transformation of the maritime sector signifies a fundamental shift from traditional operational practices based on experience to data-driven decision-making frameworks supported by simulation. The integration of computational tools, real-time monitoring systems, and artificial intelligence-based analytics has fundamentally altered how maritime organizations approach the design, manufacturing, operations, and maintenance of equipment (Mao et al., 2025).

The significance of this analysis lies in the comprehensive examination of how modern software solutions address the numerous challenges faced by the maritime industry. By exploring both established technologies and emerging applications, this study seeks to provide a detailed understanding of the technological landscape and evidence-based benefits of software integration in maritime processes through the creation of an integrated guide to simulation software used in each branch of the maritime industry as previously described.

The journey of digital transformation in the maritime industry has progressed through several distinct phases. The foundational phase began with the introduction of Computer-Aided Design (CAD) and basic computational tools in the 1980s and 1990s. The second phase, spanning the 2000s, witnessed the emergence of specialized maritime software, including hydrodynamic analysis tools and naval architecture-specific applications. The current phase, characterized by the adoption of Industry 4.0, emphasizes integrated systems, real-time data analysis, and cybernetic control of maritime operations (González-Cancelas et al., 2025).

The transition to Industry 4.0 in the maritime domain has been primarily driven by the need to optimize increasingly complex supply chains, reduce environmental impact, and enhance operational safety (Gazzaneo et al., 2025). Contemporary maritime software applications now incorporate advanced features, including machine learning algorithms, integration of Internet of Things (IoT) sensors, cloud computing infrastructure, and AI-based decision support systems.

Digital Twins (DT) technology has emerged as a transformative paradigm in maritime operations, enabling unprecedented levels of simulation, analysis, and real-time control by creating virtual replicas of physical maritime systems (Zeneli et al., 2024). Digital Twins operate by integrating data from multiple sources - including sensors, operational records, and simulation models - to create comprehensive virtual representations that mirror the behavior and characteristics of their physical counterparts.

The architectural framework of Digital Twins in maritime applications typically encompasses several key components. The physical data layer captures real-time information through IoT sensors and other monitoring systems. The virtual model layer includes high-fidelity simulations of targeted resources and maritime processes (Huri et al., 2025). The analytic layer applies machine learning algorithms, optimization, and advanced analyses of this integrated data. Finally, the decision support layer translates these analytical insights into actionable recommendations for operational improvement (Isi et al., 2024).

3.5. Comparison of identified software for each branch of the maritime industry

The identified paramount and extensively utilized software for simulating maritime industry processes will be compared based on their characteristics, applications, and performance outcomes for industry advancement. The most advanced and crucial simulation software impacting maritime industry development can be compared within specific branches as follows:

I. Naval architecture software:

i. MaxSurf vs. NAPA vs. AutoShip:

MaxSurf by Bentley Systems provides a comprehensive suite for ship hull surface modeling, hydrostatic analysis, and resistance prediction, costing over 20,000 USD/year. In contrast, NAPA operates as an integrated maritime engineering platform with complete ship life cycle design capabilities, automatically generating the vessel's hull form and structural arrangements in a 3D format, costing over 50,000 USD/year. Conversely, AutoShip offers specialized professional capabilities for hull modeling and hydrostatic calculations.

ii. DELFship vs. Orca3D:

DELFship and Orca3D are software solutions for ship design and stability analysis. DELFship provides a user-friendly platform with 88% accuracy in ship stability modeling, cost-effectiveness, and educational versions. Orca3D, an extension of Rhinoceros 3D, offers advanced capabilities including Computational Fluid Dynamics (CFD) analysis resulting in 2-4% drag reduction and 7-10% lift enhancement, suitable for budget-conscious projects.

II. Software used for computer fluid dynamics simulation:

iii. ANSYSFluent vs. Star CCM+ vs. OpenFOAM:

The ANSYS Fluent is a leading commercial CFD platform, with significant presence due to its comprehensive modeling capabilities for determining drag coefficient and analyzing ship body flow, boasting a reliability of 94% in resistance simulations with an average error of 3.5%, and an average simulation time of 8.5 hours at a cost of 35 euros per hour. On the other hand, Star CCM+ serves as a comprehensive CFD platform enabling modeling of various fluid phenomena, featuring a reliability of 92% in hydrodynamic analyses, an average simulation time of 10.2 hours costing 42 euros per hour. In contrast, the software OpenFOAM offers a free and open-source CFD platform (with support available at 8 euros per hour) that has gained significant adoption within maritime engineering communities, particularly appealing to organizations with limited budgets (capturing 22% of the market), exhibiting an 88% reliability but with a relatively high error rate of 5.1%.

iv. FINE^{TM}/Marine vs. Cadence Fine Marine:

The software FINE^{TM}/Marine, developed by NUMECA International, is a specialized CFD environment tailored for maritime applications, incorporating automatic free surface capture and propeller-body interaction modeling, boasting a 95% reliability rate (the highest), 2.8% error for resistance simulations, and an average simulation time of 7.1 hours. Cadence Fine Marine provides advanced CFD simulation capabilities with virtual towing functionality, significantly reducing testing costs by 40% compared to physical testing, and ensuring a reliability of 93%.

III.Software used for port operations using discrete event simulations:

v.FlexSim vs. AnyLogic vs. Arena:

FlexSim is a widely used discrete event simulation software for maritime port operations (holding a 55% market share), enabling comprehensive modeling and optimization of container terminal logistics. Studies have shown a 28.7% cost reduction in hybrid simulation-optimization scenarios.

AnyLogic, (capturing 42% market share - growing due to its versatility), operates as a comprehensive multi-paradigm platform (DES, System Dynamics, Agent-Based) supporting agent-based simulation system dynamics modeling, offering superior flexibility by combining various methodologies. At San Giorgio terminal, AnyLogic implementation led to a 20% throughput improvement.

Arena software provides discrete event simulation capabilities tailored to port operations, with the ability to adjust probability distributions for detailed representation of operational variability, incurring costs exceeding 30,000 USD annually.

vi. WITNESS Horizon vs.SIMIO:

WITNESS Horizon combines queueing theory and Petri nets for container terminal operations, while SIMIO, object-oriented, enables rapid modeling at around $50,000/year.

IV. Software used for hydrodynamic analysis:

vii.ANSYS AQWA vs. OrcaFlex:

Both software packages were applied to analyze a rectangular floating structure, showing results within 1% difference. However, in a different simulation scenario, OrcaFlex reported 40-50% higher results than ANSYS AQWA, indicating significant discrepancy.

V. Simulation software using digital twin platforms:

viii.Digital Twin Yard (DTYard) vs. Open Simulation Platform (OSP):

The Digital Twin Yard provides an ecosystem for maritime modeling and digital simulation utilizing open-source components. Recent research illustrates the integration of digital twins with deep reinforcement learning for collaborative planning in automated terminals.

Selecting simulation software to address specific issues within a company operating in the maritime industry depends on the particular application. Therefore, the most significant software options have been detailed and classified to facilitate comprehension and application, aiding decision-making in choosing suitable software for enhancement or elimination of identified problems. For complex port operations, AnyLogic and FlexSim offer superior flexibility by combining multiple simulation paradigms. For hydrodynamic analysis, ANSYS Fluent and OpenFOAM provide robust options with distinct cost and capability advantages. Software employing digital twins like DTYard embodies the future by integrating AI and real-time data for adaptive optimization.

Table 4. Classification and characteristics of the most used simulation software in the maritime industry

No.	Simulation Software	Category	Manufacturer	License	AI Integration
1.	**MaxSurt**	Naval Architecture	Bentely Systems	Commercial	No
2.	**NAPA**	Naval Architecture	Napa	Commercial	Partial
3.	**AutoShip**	Naval Architecture	Proprietary	Commercial	No
4.	**DELFShip**	Naval Architecture	Proprietary	Commercial	No
5.	**Orca3D**	Naval Architecture	Rhinoceros Extension	Commercial	No
6.	**ANSYS Fluent**	CFD	ANSYS	Commercial	Yes
7.	**Star CCM+**	CFD	Siemens	Commercial	Yes
8.	**OpenFOAM**	CFD (open-source)	Open-source	Open-source	Yes
9.	**FINE™/Marine**	Maritime CFD	NUMECA International	Commercial	Partial
10.	**Cadence Fine Marine**	Maritime CFD	Cadence	Commercial	Partial
11.	**FlexSim**	DES – Port Operations	FlexSim Software	Commercial	Yes
12.	**AnyLogic**	DES – Multi-paradigm	AnyLogic	Commercial	Yes
13.	**Arena**	DES	Rockwell Automation	Commercial	Partial
14.	**WINESS Horizon**	DES – Terminal	WITNESS	Commercial	Yes
15.	**SIMIO**	Object-Oriented DES	SIMIO	Commercial	Yes

The primary areas of innovation in the maritime industry with a horizon set for achievement by the year 2035 through the application of emerging methods and simulation software will be as follows:

*I.*According to IMO 2050, the top priority is decarbonization through the optimization of ship hull forms using Computational Fluid Dynamics (CFD), the planning of significantly more efficient routes with the aid of Discrete Event Simulation (DES), and predictive energy management through Artificial Intelligence (AI).

*II.*In line with the concept of autonomous ships by 2035, the development of algorithms for autonomous navigation, the establishment of permanent naval operation centers for remote vessel control, real-time application of simulations using digital twins for optimal decision-making.

III. Sustainability across all maritime industry activities through circular economy simulations, waste management optimization for industry functioning, and emissions monitoring through simulation software.

IV. Global supply chain resilience with DES methods for predictive planning of port congestion scenarios and other situations, utilizing artificial intelligence algorithms and machine learning to recalculate maritime routes for optimal solutions in avoiding congestion issues and ensuring smooth logistical supply chain operations.

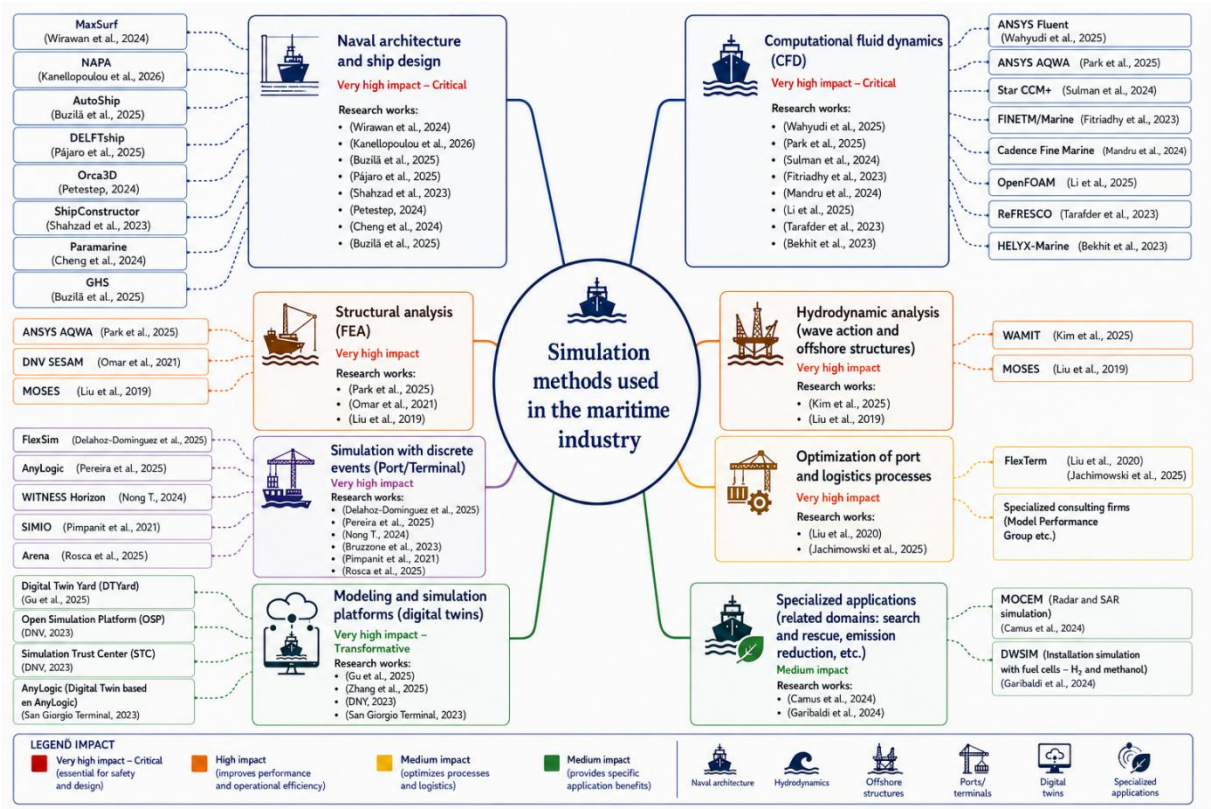


Figure 9. Integrated outline of the most important simulation software in the maritime industry – schematization of the information researched by the authors

Figure 9 depicts the essence derived from the current research, successfully consolidating information on the branches of the maritime industry utilizing specific modeling and simulation software, along with other modern techniques, to develop in the most efficient manner possible. It identifies the software used by each branch under study and a crucial aspect is the identification of significant studies based on the methodological use of the respective software. All identified articles are listed in the bibliography section, and for each modeling and simulation software, at least one representative article has been identified in the specialized literature. Moreover, the level of impact on the maritime industry branch resulting from the use of these software tools is discussed, emphasizing their contribution to process optimization and operational efficiency within the mentioned sector.

4. Results and limitations

4.1. Results of the study

In order to succinctly highlight the findings of the current study, they have been structured into five main result-oriented directions, as follows:

A. Quantified benefits of software implementation

The integration of advanced software solutions has yielded measurable improvements across various dimensions of the maritime industry:

i. *Operational Efficiency:* Documented efficiency increases ranging from 25-40% have been noted, varying based on the maturity of implementation and application domain;

ii. *Predictive Maintenance:* The implementation of Digital Twins has led to a 39% reduction in downtime, decreasing from an average of 18.6 hours to 11.4 hours monthly;

iii. *Production Quality:* In manufacturing and shipbuilding operations, the utilization of digital solutions has resulted in defect rate reductions between 40% and 49%;

iv. *Energy Consumption*: S Decreases of 12-15% in energy consumption have been reported without compromising quality or performance, supporting sustainability objectives;

v. *Testing Cost Reduction*: Software such as Cadence Fine Marine has demonstrated a 40% decrease in testing costs compared to physical tests.

B. Technological evolution and growth projections (2010-2035)

Retrospective analysis and forecasts indicate a profound transformation in M&S methodologies:

I. 2030 Projections:

i. *CFD/FEA:* Growth from 42% (in 2024) to 52%;

ii. *Digital Twins:* Growth from 22% (in 2024) to 35%;

iii. *AI/Machine Learning:* Exponential expansion from 1% (in 2024) to 10%;

iv. *Traditional Methods:* A decrease in their usage is estimated to be under 3%.

II.Horizon 2035 (research publication growth rate):

i. *AI-based methods* are projected to have the highest growth, approximately 329%;

ii. *Digital Twins* are expected to follow with a growth of 147%;

iii. *CFD/FEA methods and Maritime Simulators* are anticipated to grow by 73% and 51%, respectively.

C. Innovation priorities and integrated strategies

By 2035, innovation will focus on four strategic pillars to achieve safety and efficiency objectives:

i. *Decarbonization (IMO 2050)*: Based on optimizing hull forms through CFD, efficient route planning through DES, and predictive energy management using AI;

ii. *Autonomous Ships*: Development of autonomous navigation algorithms and permanent naval operation centers, supported by real-time simulations through Digital Twins;

iii. *Sustainability*: Application of circular economy simulations, emissions monitoring, and waste management optimization;

iv. *Supply Chain Resilience*: Utilization of AI/ML for route recalculations and DES methods for predicting port congestion.

D. Status and impact of industrial software

The software market is dominated by specialized solutions with varying impacts on process optimization:

i. *Port Operations*: FlexSim leads the market (55%), followed by AnyLogic (42%), the latter experiencing growth due to its multi-paradigm versatility. Implementing AnyLogic at the San Giorgio terminal improved throughput by 20%;

ii. *Design and CFD*: ANSYS Fluent provides 94% reliability in resistance simulations, while FINE™/Marine achieves the highest reliability (95%). OpenFOAM holds a 22% market share, preferred by organizations with limited budgets due to its open-source nature;

iii. *Naval Architecture*: MaxSurf and NAPA are dominant solutions, with NAPA offering integrated capabilities for the entire ship lifecycle at a higher cost (>50,000 USD/year).

E. Methodological convergence trends and challenges

The maritime industry is moving towards a holistic and digitized approach:

i. Deep Integration: Fusion of CFD + DES + AI methods into unified platforms with centralized data storage and onboard processing capabilities;

ii. Real-time Decision Making: Employing simulations with high credibility rates based on short-term forecasts for rapid operational decisions;

iii. Identified Gaps: Future research needs to address the requirement for scalable validation methods, more faithful integration of human factors, and management of uncertainties related to climate change and technological transitions.

Analysis of studies shows measurable benefits of implementing simulation software, such as:

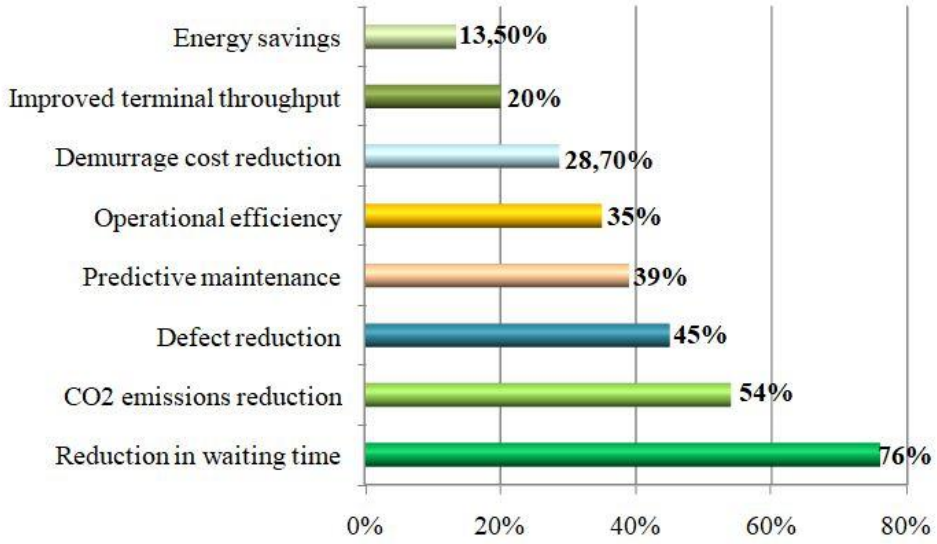


Figure 10. Measurable benefits for the maritime industry from implementing simulation using specialized software

4.2. Limitations of the Study

While this review offers an extensive synthesis of maritime modeling and simulation, several methodological limitations must be noted:

i.Database & Language Scope: The literature search was restricted to indexed English-language academic journals and conference proceedings across five primary databases. Proprietary technical reports, non-English publications, and undisclosed commercial industry datasets were not evaluated.

ii.Software Profiling Constraints: Data regarding software parameters, licensing fees, and market share (e.g., FlexSim 55%, OpenFOAM 22%) were compiled from 45 public profiling platforms and published case studies, which may be subject to commercial updates.

iii.Exploratory Forecasting Assumptions: The publication growth figures projected for 2026–2035 (+329% for AI, +147% for Digital Twins) represent exploratory baseline scenarios derived from historical publication trajectories. They do not account for unpredictable market disruptions, regulatory shifts, or technological bottlenecks, and should be interpreted as directional trends rather than validated deterministic forecasts.

5. Conclusions and future research directions

Over the past two decades, modeling and simulation methods have emerged as essential tools in the maritime industry, enabling the exploitation of operational potential and the optimization of complex processes. The evolution of these methods signifies a clear progression from traditional approaches towards integrated solutions that incorporate emerging technologies. Discrete event simulation has become the most utilized methodology for maritime processes, especially those involving queuing systems and resource allocation, followed by system dynamics and hybrid methods that allow a more

comprehensive representation of complex system behaviors. Each of these methodologies offers distinct perspectives on operational efficiency, ranging from detailed operations at port terminals to long-term strategic evaluation of maritime industry policies and capacities.

Simulation software has significantly advanced, reflecting shifts in research priorities and capabilities. Between 2010 and 2020, maritime simulators and CFD/FEA methods dominated research in the naval industry, providing high precision and scientific validation for design and operational processes. These tools have enabled specialists to explore complex scenarios without disrupting actual activities, thereby reducing costs and risks. Nonetheless, limitations in these traditional approaches, such as implementation complexity and high computational costs, have paved the way for innovative methodologies. Integrating data from multiple sources and combining different simulation paradigms have led to a more realistic representation of maritime systems, allowing for the emergent analysis of behaviors that could not be captured by individual models.

The transition to emerging technologies has marked a decisive turning point in how researchers and practitioners address issues in the maritime industry. Digital twins, with an annual adoption growth of approximately 25% from 2020 to 2022, have been recognized for their potential to support predictive maintenance, intelligent shipping, and offshore energy systems. Concurrently, AI-based methods have rapidly accelerated, integrating generative artificial intelligence and machine learning into various maritime applications, from naval traffic forecasting to optimizing processes at maritime terminals and autonomous navigation. This convergence between traditional methodologies and emerging digital technologies is not a simple substitution but rather a profound complementarity that enhances operational analytics capacity.

Explainable artificial intelligence and language models represent a new frontier in research. These technologies can provide transparency in machine learning decisions, building trust and supporting regulated acceptance of autonomous systems. Enhanced digital twin platforms with AI capabilities can deliver predictive maintenance, operational optimization, and integrated decision support within maritime processes. Quantum optimization algorithms promise a solution for large-scale maritime optimization problems that are challenging for classical computers, such as fleet routing and terminal scheduling, while transfer learning enables models trained on historical data to quickly adapt to new vessels or operational contexts with limited additional data.

Real-time implementation of predictive models in decision support systems or digital twin environments remains a critical priority. As the maritime industry progresses towards intelligent and sustainable port ecosystems, the role of modeling and simulation will amplify, and integration with AI-based methodologies will become not only a competitive advantage but an operational necessity. The success of this transition depends on a balanced approach that combines the theoretical rigor of traditional models with the predictive power and adaptability of emerging technologies, all within a framework explicitly anchored in the operational realities and practical constraints of the maritime industry.

Discrete event simulation, optimization methods, and agent-based modeling have proven effective for operational processes, including port terminal operations, vessel traffic management, and supply chain logistics. Traditional modeling and simulation methods such as maritime simulators and CFD/FEA methods have dominated research in the naval industry, at least for a decade, between 2010 and 2020, but emerging technologies (such as digital twins and AI-based methods) have rapidly gained ground starting in 2020, reflecting the accelerated digitalization trend in the maritime industry across all domains and an increasingly significant academic impact. Moreover, from an industrial relevance perspective, the maritime industry's reliance on modeling and simulation techniques to keep up with safety, efficiency, and compliance requirements is evident.

Modeling processes in the maritime industry continue to evolve towards greater integration, incorporating multi-physics simulations, economic analyses, environmental assessments, and risk evaluations within unified decision support frameworks. The shift from isolated process optimization to holistic system-level modeling allows for identifying trade-offs and synergies across traditionally

separate domains. Machine learning and artificial intelligence increasingly complement traditional modeling approaches, providing data-driven insights and automation capabilities.

Future research directions crystallize around several converging axes. One direction leans towards deeper integration of human factors and organizational behavior into process models to capture decision-making and adaptation realistically. Uncertainty quantification and robust optimization methods remain key challenges, especially for long-term scenarios that must consider the impact of climate change and technological transitions in the industry. A second direction involves large-scale validation of process models and digital twins on real operational data to ensure reliability and practical applicability in diverse operational environments.

Moreover, future research should address several key challenges. Firstly, scalable methods are needed for validating process models on a large scale and digital twins against operational data to ensure reliability. Secondly, human factors and organizational behavior require better integration into process models to capture decision-making and adaptation realistically. Thirdly, uncertainty quantification and robust optimization methods need further development to address deep uncertainties in long-term scenarios.

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List of abbreviations:

ABM – Agent-based modeling
ABS – Agent-Based Simulation
AIS – Automatic Identification
CAD – Computer-Aided Design
CFD – Computational Fluid Dynamics
CII – The Carbon Intensity Indicator
DES – Discrete Event Simulation
ECA – Emission Control Area
EEDI – Energy Efficiency Design Index
FEA – Finite Element Analysis
FEM – Finite Element Method
FVM – Finite Volume Method
hub-and-spoke – is a transportation system designed to maximize efficiency by routing goods through a central, strategic location ("hub"), rather than directly from origin to destination (point-to-point)
LNG – Liquefied Natural Gas
M&S – Modeling and Simulation
MASS – Maritime Autonomous Surface Ships
MBD – Multi-Body Dynamics
MDTO – Maritime Digital Twin Ontology
MET – Marine Education and Training
ML – Machine Learning
QRA – Quantitative Risk Assessment
RCM – Reliability-centered maintenance
SAR – Search and Rescue

SD – System Dynamics
STPA – Systems-Theoretic Process Analysis
VTS – Vessel Traffic Service

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