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AGENT-BASED MODELING APPLICATIONS FOR SUSTAINABLE SHIPPING AND PORT INFRASTRUCTURE DESIGN AND ANALYSIS

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ABSTRACT

The maritime industry is a major player in global transportation, providing reliable and efficient freight services, but also a major contributor to greenhouse gas (GHG) emissions. The International Maritime Organization is discussing stringent GHG policy measures (e.g., Net-Zero Framework) to decarbonize shipping. The World Association for Waterborne Transport Infrastructure also declares its full commitment to supporting the energy transition. This study provides an overview of applying agent-based model (ABM) simulation tools to enable GHG emission reductions from maritime transport systems, including ships, infrastructure, and navigational resources. Agent-based simulation models are powerful tools that model complex real-world systems through the interactions of agents and the environment(s). The behaviors of agents adjust and emerge from these interactions, providing flexibility for testing policies and their implications under realistic conditions. This review considers different applications of ABM in maritime systems – ships, port infrastructure, and the combined systems. The study demonstrates the significant potential of ABMs to analyze and improve the performance of complex systems with high uncertainty in the waterborne sector. Particularly, ABMs were found useful for real-world applications in polar, offshore, and inland shipping. The review shows significant trust among maritime stakeholders in ABMs and their willingness to commit time and resources to their development.

Keywords: agent-based simulation, sustainable shipping, sustainable ports, icebreakers, inland navigation

NOMENCLATURE

ABM	agent-based model
AIS	Automatic Identification System
DEM	discrete-event model
DS	dynamic system
FSWNS	the Finnish-Swedish winter navigation system
GHG	greenhouse gas
GIS	geographic information system
LNG	liquid natural gas
SD	system dynamics

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WASP	wind-assisted ship propulsion
Ro-Ro	roll-on/roll-off
Ro-Pax	roll-on/roll-off and passenger

1. INTRODUCTION

The waterborne transportation sector has a high responsibility to reduce greenhouse gas (GHG) emissions, considering its dominating position globally in terms of transported goods compared to other transport modes [1]. The International Maritime Organization and the World Association for Waterborne Transport Infrastructure have expressed their full commitment to decarbonizing shipping. In line with these efforts, there is a need for effective decision-making tools for the design and analysis of sustainable waterborne transport systems, including fleets, port and navigational infrastructure, and their operational strategies. The development of new simulation models for waterborne transport systems is one promising direction, which can range from general-level models for policymaking [2] to highly detailed digital twins [3–5]. There are many different classifications of simulation approaches that group them by the level of detail, practical applicability, and the level of determinism [6,7]. For the means of the present study, we use a classification shown in Fig. 1. This classification is common in simulation science [8,9] and divides approaches into dynamic systems (DSs), system dynamics (SD) models, discrete-event models (DEMs), and agent-based models (ABMs).

A **DS** is a classic model developed in physics and engineering, commonly based on a series of differential or algebraic equations from first principles/engineering relationships, and numerical methods like computational fluid dynamics and finite element method. The state variables are physical or technical (e.g., speed, pressure, thrust), and typical outputs are detailed trajectories and performance under scenarios [10,11]. DS models are mainly used in highly specialized, local, and often theoretical applications. **SD** is a modeling methodology designed to support strategic and policy decisions in complex, large-scale systems [12–14]. SD represents the system as aggregated stocks (accumulations at the system level, e.g., revenues, fuel supply capacity, infrastructure capacity), and flows (rates of change such as adoption, retirement, investment, learning, and delays). The approach focuses on how feedback loops and time delays **generate** endogenous behavior and long-run dynamics, rather than detailed local trajectories.

Discrete-event simulation models a process as a chain of events progressing over time. Connections and blocks in the flowchart determine how passive entities (or batches of entities) move through the process and how their states change. Blocks can represent queues, delays, or the processing of entities by resources with a specific service performance. In DEM, all entities of a specific type are identical without individual characteristics. In addition, the behavior of an entity within one block stays unchanged until the entity progresses to another block. DEM is a natural choice for modelling conveyor-like systems, e.g., manufacturing lines, call centers, and regular transport chains [15,16]. The common trait of DSs, SD models, and DEMs is their emphasis on temporal continuous progression and causality – they progress over time and can be stopped at any state of the model progression, showing the corresponding values of the model variables at any moment.

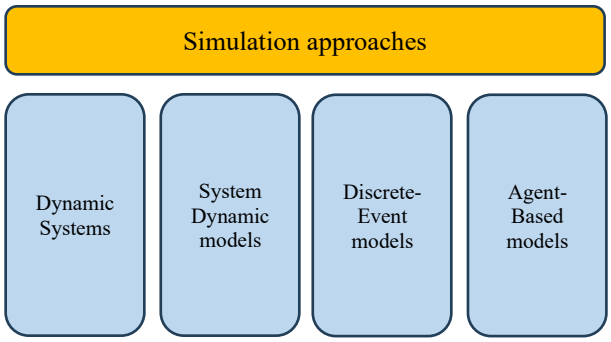


FIGURE 1: A CLASSIFICATION OF SIMULATION APPROACHES

In **ABM,** the performance of a complex system is modelled through the dynamic behavior of its agents. Agents may represent individuals (e.g. people, animals), organizations, or engineered entities such as vehicles, machines/robots, components, or products. The agents have state variables, and they follow a set of individual rules. Complex system-level dynamics can emerge from these micro-level interactions, allowing researchers to explore macro behavior without imposing a closed-form aggregate representation. Additionally, ABM allows for considerable flexibility in model upgrades, whether it involves the development of additional functionality or adjustments to the model logic. The model can be upgraded by locally changing the behavior of specific agents or the environment, without the need for reconsideration of its systemic assumptions and logic.

In transportation planning, ABM is often used to represent the decisions and interactions of travelers, vehicles, and operators at scale. Such models may be highly data-driven and may incorporate optimization routines and post-hoc analysis to evaluate system performance under alternative policies or scenarios [17,18]. ABM is also used to build interactive "digital twins" of real or proposed systems, where the focus is on process realism, temporal progression, and explicit causal logic at the agent level [4,19–21]. ABM provides advanced tools for "what-if" analysis and significant capabilities in scenario testing, debugging, and verification.

Simulation tools for the energy transition in waterborne transport should capture system interactions between vessels, fuels, port services, and infrastructure, because technology adoption changes operational feasibility, reliability, and overall efficiency. In particular, many decarbonization options depend on the ship-infrastructure interface (e.g., fuel availability, bunkering/charging constraints, turnaround times, and port resource allocation). Under these conditions—where technologies are evolving and empirical evidence is still limited, ABM is attractive because it can represent heterogeneous decision-makers and operational actors explicitly (e.g.,

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shipowners, port operators, service providers) and explore how their interactions shape system-level outcomes. This supports "what-if" analysis of transition pathways and policy instruments, while making behavioral and operational assumptions transparent. Despite the potential benefits, ABMs for waterborne applications are still limited [22–24].

This study reviews existing research experience of applying ABM to model energy use and GHG emissions from maritime transport systems, including our own developments. The papers studied are published across a wide range of journals and conference proceedings, e.g., Journal of Information Management, Transportation Research, Ocean Engineering, Environmental Innovation and Societal Transitions, Marine Policy, Technological Forecasting & Social Change, Maritime Transport Research, International Journal of Shipping and Trade, Transport Problems, Journal of Marine Science and Application, International Shipbuilding Progress, proceedings of the Winter Simulation Conference, and other proceedings of relevant conferences and workshops.

In addition, we discussed two of our agent-based frameworks developed for different tasks – simulation of winter navigation in cold regions [25,26], with a focus on optimal utilization of icebreaker resources, and simulation of battery-driven inland navigation in Europe [27], with a focus on estimating energy demand and required charging infrastructure. They are deeply integrated with a geographic information system, providing highly accurate spatial data on the geometry of water bodies – oceans, seas, rivers, and lakes.

The ABM contributions identified in these papers can be classified into three categories: (i) sector-level transition and policy analysis for shipping decarbonization, (ii) port-centered infrastructure and decision-making, and (iii) operational modeling of maritime logistics and vessel energy use (Fig. 2).

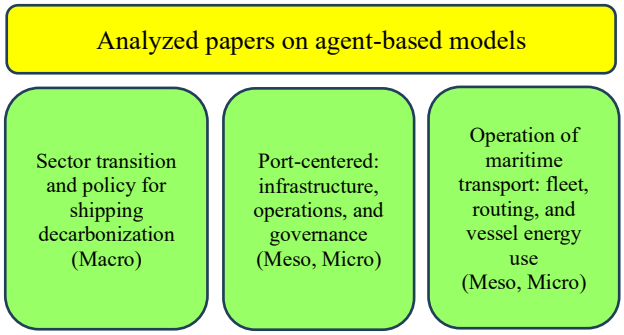


FIGURE 2: A CLASSIFICATION OF THE ANALYZED PAPERS BY AREA OF CONTRIBUTION

Our own contributions belong to the third category and focus on developing interactive modeling frameworks that support the analysis of temporal continuous progression and causality within the studied waterborne transport system. They can be considered early prototypes for the operational logic of future autonomous versions of the transport systems studied, as the decision-making logic of ships in the model is individual and based on up-to-date knowledge about the system state. However, the security and safety aspects of autonomous systems are outside the scope of the studied logic of transport operations.

The remainder of the paper is organized as follows. Section 2 provides an overview of macro-level ABMs studying green transitions in the maritime sector and related policies. Section 3 reviews existing meso- and micro-level ABMs studying port infrastructure, operations, and governance. Section 4 concentrates on the meso- and micro-level ABMs studying operational aspects of maritime transport – fleet, routing, and vessel energy use, followed by the Discussion and Conclusion.

2. Sector transition and policy AMBs for shipping decarbonization

The Fraunhofer Institute for Systems and Innovation Research conducted one of the most systematic works for the development of ABMs – the CLEANSHIP [28] and the MATISSE-SHIP [29] – to support policymaking in the sustainable transition of shipping. Driven by the so-called Brundtland Report [30], the early project team emphasized the need to develop technologies to reduce air pollution from shipping. In addition to environmental sustainability, such technologies must be practically feasible and economically efficient. Correspondingly, the authors proposed a conceptual idea of an ABM for the simulation of the investment process in sustainable technologies for deep-sea shipping [31]. The ABM is implemented in the MASON simulation environment (Java). It divides agents into shipbuilders and shipping companies. The demand comes from customers (shippers and logistics companies). The ABM has a time step of one year and simulates how agents interact to estimate demand, supply, projected prices of transportation and ships, investments in R&D by shipyards, and the adoption dynamics of different sustainable technologies.

The concept explores the idea that, unlike most other transportation modes, a single player can significantly affect the shipping market due to its high level of globalization and the limited number of major actors. The authors state that radical changes towards sustainability are required, and these changes should start in the sectors of the shipping industry that are already prone to innovation. Thus, it is reasonable to explore opportunities to decarbonize shipping by encouraging influential early adopters. The model was extended to account for wind-assisted ship propulsion (WASP) [28], a wider selection of green fuels [29], stakeholder assessment of transition scenarios [32], and the possibility of ship retrofitting [33].

Bas et al. [34] developed a more detailed ABM to study how different policies affect the green transition in shipping. The study introduces a term for a maritime fuel system – the physical assets and organizations that produce, distribute, and consume fuels – and applies a holistic, dynamic perspective to capture the complex relationships within this system. Figure 3 [34] shows different agents, objects, connections, and interactions used in the model. The vessels navigate to deliver cargo along the routes between the ports, consuming a certain quantity of fuel corresponding to the energy demand and the route length. Each route has its specified emission limit.

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The model employs an advanced procedure to select a cargo assignment based on cargo demand, availability, and fuel cost in the port, shipment size, and the allowed emission limit on the route. Additionally, the vessel considers a retrofitting option for a different fuel once a year, based on economic considerations and fuel availability at the ports. The authors demonstrated the model capabilities by assessing three policies – introducing strict control of ship emissions with enforced emission limits and penalties for violators, extending the supply of green fuels in ports, and enforcing the retrofitting of ships. A case study is presented for liquid natural gas (LNG) as a green fuel, for which a steady supply is indicated as the most crucial factor for LNG adoption.

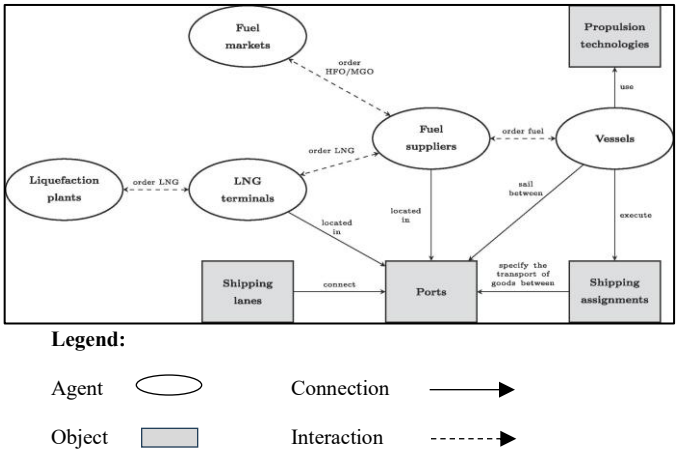


FIGURE 3: AGENTS, OBJECTS, CONNECTIONS, AND INTERACTIONS USED IN THE MODEL BY BAS ET AL., ADAPTED FROM [34].

Karslen et al. [35] proposed an ABM to simulate the effects of climate-energy policies on the adoption of wind-assisted ship propulsion systems in the dry bulk time-charter market. The study applies the Multi-Level Perspective [36] – a sociotechnical framework for studying sustainability transitions and the diffusion of innovations, which combines the methods from evolutionary economics, sociology, and technical disciplines. The authors identified that split incentives are the primary barriers to WASP adoption – shipowners invest in the technology, but charterers reap the benefits from reduced energy consumption. The study recommends a coordinated package of measures to mitigate the split incentive barriers: carbon pricing, higher effective fossil-fuel prices, and publicly funded, large-scale pilot demonstrations of WASP technologies. The topic is further advanced by Chica et al. [37] and Romero et al. [38], who considered real-world data on technology costs, emission reduction potential across technologies, vessel characteristics, and the effects of targeting micro-level incentives at a limited number of influential early adopters.

Buermann et al. [39] introduced an ABM framework that assesses decarbonization policies and their impacts on shipping company operations. The framework aims to reduce GHG emissions, supporting a profitable and non-disrupted industry. Figure 4 [39] shows the principal scheme of the framework, where agents are classified into traders, regulators, fleet operators, fleet owners, and vessels. The Market generates the cargo demand based on statistical distributions, and the cargo is transported by Vessels operating in the Environment. The study emphasizes the significant flexibility of the framework supported by its modular and scalable design. Each vessel is described by a set of parameters, such as the type of cargo, capacity, fuel type, allowed speed range, and corresponding fuel consumption. The model specifies the annual values of the carbon tax and the carbon emission targets. The economic calculations consider the available budget, energy-efficient technologies with costs, the energy density price, and emissions for different fuels. The authors demonstrated significant capabilities of the framework in finding the most cost-effective policies to meet climate targets.

A similar ABM approach was developed by Nonomura et al. [40] to study the feebate policy proposed to the International Maritime Organization by Japan. The feebate policy is a fee-and-rebate (levy-and-rebate) mechanism intended to narrow the gap between fossil fuels and zero-emission fuels by charging fossil fuels and rebating zero-emission fuels. The study indicated that a rebate is highly efficient for transitioning to ammonia when applied early.

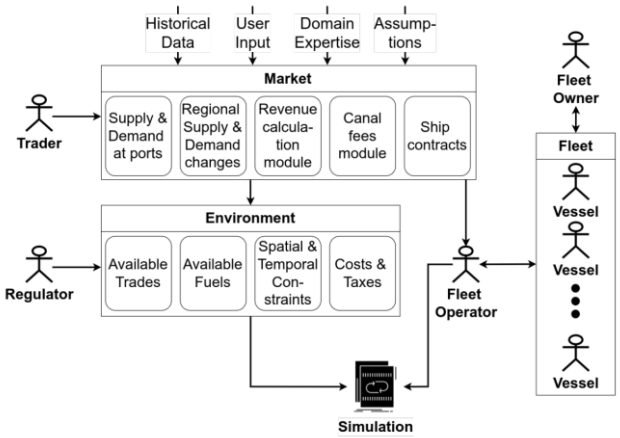


FIGURE 4: A PRINCIPAL SCHEME OF THE ABM FRAMEWORK BY BUERMANN ET AL. [39].

3. Port-centered ABMs: infrastructure, operations, and governance

ABMs for greener ports study the specifics – technological, organizational, and operational – of ports, terminals, quays, berths, and ships operating in their area to achieve high energy efficiency, smooth vessel traffic planning, and delay minimization. Better port planning enables significant GHG reduction from ships through slow steaming [41]. Existing research concentrates on developing ABMs for container terminals [22,42–47], Ro-Ro (roll-on/roll-off) and Ro-Pax (roll-on/roll-off and passenger) terminals [48], coal terminals [49], liquid bulk terminals [50], and entire ports [51–55]. Ro-Pax ships transport mainly wheeled vehicles and passengers. They hold

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strategic importance in moving people and goods due to their access to shorter routes and deep integration with intermodal transportation systems.

Figure 5 is a schematic of the main elements of a container terminal. After a container ship arrives at the anchorage or prepares to depart, port tugs assist with safe and efficient mooring operations at the berth. Quay cranes then unload containers, which are then transferred by terminal trailers for storage in the container yard. The terminal trailers and the quay cranes are also responsible for processing outgoing containers. The quay or the nearby terminal area is typically equipped with bunkering or electricity supply infrastructure for container ships. The container yard cranes arrange the newly arrived containers within the yard and rehandle containers – rearrange the stored yard containers to reach a specific outgoing container. Reach stackers complement yard cranes to assist with minor container operations. Some large container ports are equipped with railroad connections – in this case, container yard cranes are also responsible for delivering containers from the yard to the railroad.

Container trucks connect the terminal to the inland transportation network, picking up and delivering containers from and to the terminal. Access to the terminal is organized through the terminal entry gate. The container terminal logistics framework consists of operations, scheduling, and information systems. The terminal quay and container yard are very limited resources and require reliable planning.

Li and Li [42] proposed an ABM using the Harvard computer architecture to simulate the logistics of a container terminal. Harvard architecture enables better computational performance by utilizing separate memory for program instructions and data. Agents in the model are classified into resources – anchorage, tugs, berths, quay cranes, terminal trailers, yard cranes, and entry gates, and their managers – planners and schedulers. The simulation is driven by the traffic of ongoing and outgoing containers. Although the ABM maximizes the number of containers processed per unit of time, the systemic model of the container terminal and specific scheduling algorithms can be used to advance the terminal operations for improved sustainability.

Another systemic ABM of a container terminal was proposed by Henesey et al. [45] for evaluating its operational policies that consider ship prioritization, berth, and container allocation. This ABM stands out due to its extensive verification and validation, which utilizes data from existing ports, sensitivity analysis, and structured evaluation by Operations Directors and managers of container terminals. The study has found that prioritizing container ships with shorter processing times results in better time-related performance for the entire terminal. A related ABM for the development of autonomous ports is proposed by Thurston and Hu [43] that schedules the terminal resources to maximize the utilization of quay cranes. Rebollo et al. [44] developed an ABM of a container terminal to support automatic container allocation.

Vidal and Huynh [22] studied how yard-crane scheduling – specifically how drayage trucks are served – can reduce their air pollution. They emphasize the relevance of the ABM concept for modelling container yard operations because port crane operators make their decisions individually. The study suggests that emissions from drayage trucks can be reduced by minimizing the queueing time of trucks at the port, thereby enhancing the supply chain efficiency. Particularly, the authors recommend prioritizing trucks closest to the cranes instead of using the typical first-in-first-out principle.

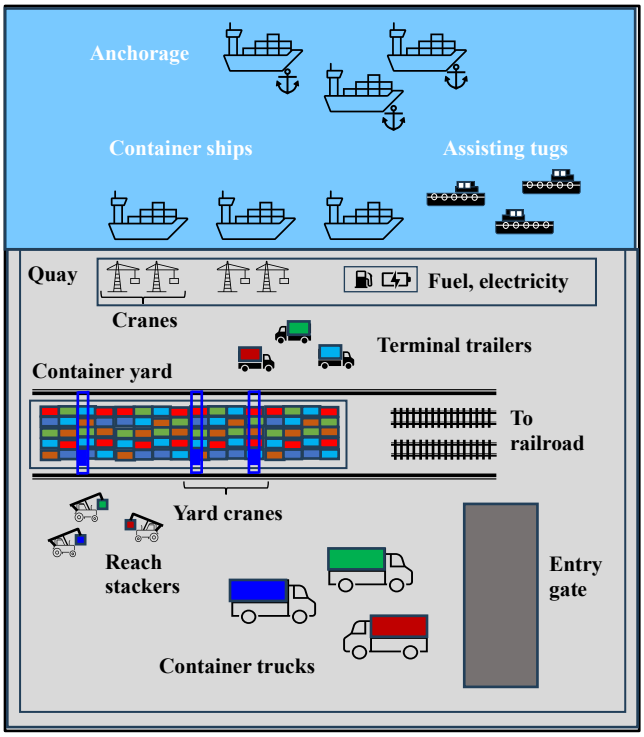


FIGURE 5: THE PRINCIPAL SCHEME OF THE CONTAINER TERMINAL ELEMENTS.

Research applications of ABMs are not limited to container terminals. For example, Habenicht [49] developed an ABM for the coal terminal operations, commissioned by the industrial port developer TAKRAF Group, and provided practical recommendations to improve the port capacity and processing time. Balaban and Mastaglio [48] developed a stochastic ABM of Ro-Pax terminal operations (Fig. 6) to assess terminal efficiency and attractiveness to passengers. Transport demand varies across seasonal and weekly cycles, and individual travelers choose between Ro-Pax and car-only travel as a function of cost, travel time, and reliability (implemented via a Bayesian network). The ABM captures terminal arrivals, queuing and lane allocation, and vehicle loading onto the ferry, while ship operations and disruptions (e.g., congestion and adverse weather) affect schedule adherence. Reliability is quantified using the frequency and duration of arrival delays.

More recent research studies primarily focus on the broader picture – they examine entire ports rather than specific terminals. For example, Senturk et al. [51] presented an ABM of the

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business processes of the Port of Genoa. It concentrates on the policy-related issues of port operations – simulation of import-related stakeholder interactions in a seaport with a high level of abstraction. The ABM specifies a broad range of agent types involved in port planning and management – Agent Maritime, Customs, Custom Clearance Agent, Delivery Service, Deliverer, Terminal, Finance Police, Gate, and Terminal Area. Agents communicate with each other through messages, exchanging goods, and planning transportation. The findings identify two bottlenecks in port operations: delay-prone processes of container handling and queue-generating documentation routines.



FIGURE 6: 3D VISUALISATION OF THE ABM SIMULATION ENVIRONMENT FOR RO-PAX TERMINAL OPERATIONS [48].

Davydenko and Fransen [52,53] developed an ABM to study the operation and scheduling of port nautical services for deep-sea ships – pilotage, towage, and mooring – during key in-port activities (arriving, departing, and berth shifting). Because these services are tightly coupled, disruptions in one service can propagate through the system and generate unplanned delays. The work was carried out in collaboration with the Port of Rotterdam, which provided the information required for model development, testing, and verification. Rotterdam's landlord governance structure and decentralised multi-operator service provision make it well-suited for an ABM representation.

Agents in the ABM include deep-sea ships, pilots, tugboats, terminals, the port authority, and the harbor master. The ABM represents both (a) information flow required for operational coordination (e.g., location, port-call requests, clearance, and resource assignment) and (b) physical flows (e.g., vessel movements, joint operations with pilots and tugs, and berth occupation). Route and service-time parameters for vessels, tugboats, and pilot boats are derived from the Automatic Identification System (AIS) data and used for model calibration, complemented by port-call data provided by the Port of Rotterdam. The model supports identification of local bottlenecks within individual service provider and assessment of coordination and collaboration measures to improve systemic efficiency.

Li et al. [55] presented an ABM for the assessment of port cluster resilience. They argued that a bottom-up, agent-based representation can capture key resilience aspects. They considered two types of agents – ports and vessels. In the model, a port can have one of the following states – "normal operation", "closed due to external disturbances", and "congested". The closed port experienced a disturbance followed by a recovery. A vessel agent can also have three different states– waiting, port operations, and moving between ports. The authors presented a case study on the impact of typhoons on port resilience, demonstrating that the port cluster of the Guangdong-Hong Kong-Macao Greater Bay Area is sensitive to typhoons.

Lastly, Muravev et al. [54] proposed an advanced, detailed ABM to optimize operations at an intermodal dry port terminal. While the methodology could be applied to the design and analysis of green shipping and sustainable port infrastructure, we do not discuss it further because dry ports fall outside the scope of the present study.

4. Operational ABMs of maritime transport: fleet, routing, and vessel energy use

The ABMs of waterborne transport systems study their performance by modelling the dynamics of independent ship operations and ship interactions with each other, ports, and offshore infrastructure. ABMs are applied when simpler approaches fail to reliably analyze complex waterborne systems with non-linear processes, a challenging environment, and individual elements with non-trivial behavior (e.g., heterogeneous decision rules, threshold effects, interactions, and adaptive responses). ABMs are primarily applied to waterborne transport systems within polar [19,25,26,56], offshore [57], and the inland transport sectors [58–60]. Additionally, some studies examine traffic management issues in piracy-prone waters [23,24].

Vanek et al. [23] proposed an agent-based decision-support tool to assess policies for managing the maritime piracy issue. The tool was developed in collaboration with and through feedback from maritime stakeholders. The ABM simulates maritime traffic, represented by merchant vessel agents, pirate activity, represented by pirate vessel agents, and countermeasures against piracy, executed by naval ship agents. All agents are placed in a detailed geographic information system (GIS) environment with specified shallow water areas inaccessible by ships. The weather model accounts for wave height, wind speed, and currents, which affect the behavior of ships and the decisions of pirates.

The pirates attack passing merchant ships using a mothership accompanied by a group of small, high-speed crafts. A merchant vessel requests help from naval ships, and naval ships provide military assistance. The cargo demand in the model is fixed and provided as an origin-destination matrix based on historical traffic densities, while routes are optimized under the environmental constraints during the model run for two goal functions: the length of the route and piracy risk. The piracy

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risk is estimated based on historical data on pirate attacks in a specific location. Allocation of a limited number of naval vessels is also optimized to cover the most merchant ship traffic within their operational radius. The pirate vessels search for potential merchant ships and then attack within their area of deployment and then attack the vessel. If a naval vessel fails to prevent the attack, or if it runs out of supplies, the pirate vessel returns to its home base. Using a case study of a potential maritime corridor in the Indian Ocean, the results show that existing successful practices of piracy prevention in the Gulf of Aden may be suboptimal in the studied region.

ABMs are particularly useful for assessing the performance and sustainability of polar waterborne transport, where ice presence is significant and seasonal. A ship needs to break the ice on its route to advance, which requires much energy and hull strength. Vessels may therefore request icebreaker assistance—a limited resource —which can reduce ice resistance or tow a ship through difficult sections. Route choice is also critical. Accordingly, ABMs of polar transport systems typically represent merchant ships and icebreakers, coupled with a dynamic spatial model of ice conditions integrated with a GIS environment, and modules for optimizing route and icebreaker assistance [56].

Our team has several studies on the modeling of polar maritime shipping. Kulkarni et al. [26] and Kondratenko et al. [61] applied an ABM to estimate the performance of the Finnish-Swedish Winter Navigation System (FSWNS). The FSWNS coordinates shipping in ice conditions in the Gulf of Bothnia and organizes icebreaker assistance. The model, developed and verified with extensive involvement of stakeholders and experts from the Finnish Transport Infrastructure Agency, simulates merchant ship traffic based on historical AIS data. The merchant ships execute voyages from the source port to the target port along the dynamic directed pathways – specific routes provided by the icebreaker, considering the relevant ice conditions. The agents – merchant ships and icebreakers – operate in a GIS environment with an advanced model of ice conditions based on data provided by the Finnish Meteorological Institute. We developed a detailed engineering database to reliably estimate the performance indicators of the WNS. The engineering database includes technical parameters of merchant ships and icebreakers, which are required for estimating their energy consumption and speed in specific ice conditions for independent navigation and for moving together as a convoy. The model simulates ship traffic in chronological order. If the speed of a merchant ship drops below a certain threshold, it requests assistance from an icebreaker operating in the corresponding area.

The ABM provides decision-making support to enhance the efficiency of the FSWNS by planning the technical parameters of icebreaker resources, allocating them effectively, and optimizing the operations of agents. The performance of the FSWNS is measured in terms of the total CO_2 emissions from merchant ships and icebreakers, the total cost of operation, and the total waiting time of the merchant vessels for icebreaking assistance. The ABM demonstrates that the optimal allocation of icebreakers is extremely effective in improving the performance of the FSWNS.

Tarovik et al. [19] proposed a digital twin of an Arctic offshore transport system to analyze the safety and reliability of a polar offshore platform and its resources. The digital twin considers the detailed ABM of the platform, support vessels, and shuttle tankers operating in ice conditions. The ABM simulates the technological processes of the platform – consumption of supplies, delivered in advance by support vessels, production routines on the platform, and the export of final products by shuttle tankers. The model was commissioned, inspected, and verified by the industrial company – the owner of the platform, which allowed for a high level of precision and reliability of the ABM. Rippel et al. [57] proposed an ABM to optimize fleet operations for offshore wind farm installation. It combines the advantages of a strategic decision-making approach with tactical algorithms that utilize historical weather data.

ABMs are also widely used for simulating inland waterborne transport systems. Shobayo and Hassel [59] developed an ABM to improve the performance of barge processing in maritime ports with inland water route connections. The primary issue is the long waiting times for barges, resulting in barge congestion that hinders the efficiency, reliability, and image of inland shipping. The model includes different agents – maritime ships, barges, terminals, and cranes with specific performance. The technical data on the agent parameters and the model logic is provided by barge and terminal operators of the port of Antwerp. The model was further validated in collaboration with stakeholders. The study finds that the primary reason contributing to barge congestion is the prioritization of maritime ship processing at the terminals, which means that barges are given the lowest priority. The model simulations demonstrated that providing separated berths with infrastructure for barges handling can resolve the issue of barge congestion and significantly improve the viability and attractiveness of inland transport.

Saldarini et al. [60] studied the prospects of electrified passenger boats in Venice. The authors specified three types of agents: a route, a boat, and a charging station. The study selects a typical vessel design – a water taxi with a capacity of up to 12 passengers – for electrification to operate on the 9.9 km route from Marco Polo Airport to San Marco Square with no intermediary stops. The authors estimated the potential battery capacity that could be accommodated within the boat, considering the design constraints. ABM simulates the energy consumption of a boat during its movement and accounts for charging at stops during passenger embarking and waiting. The charging infrastructure is charging poles with an AC power rating of 22 kW, located at the start and finish points of the route. The model calculates the ship resistance and estimates its energy consumption depending on speed. The operational profile of the ship is developed and verified with the primary stakeholder, the head of water transport in Venice. Particularly, the ABM considers the strict boat speed and acceleration limitations in Venice for four different sections of the route, and estimates its energy consumption depending on speed. The model

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demonstrated the technical feasibility of the studied transport system. The findings of the study are transferable to other routes, as the selected route is the longest in Venice.

Inland cargo shipping is one of the most promising areas for waterborne electrification [62,63] due to relatively short travelling distances compared to deep-sea shipping and the proximity of the routes to the shore. Kondratenko et al. [62] demonstrate significant electrification prospects of the Danube River inland transportation system, connecting territories of ten European countries with more than 2400 km of commercially navigable routes. Grobarcikova and Sosedova [58] discuss significant prospects of applying ABM to study the performance of the Danube River inland transportation system.

Our recent development – the modelling framework for electric inland ships – is designed to analyze their feasibility, considering the electricity and infrastructure needed for their reliable operation. The framework provides a realistic model of inland maritime transportation with detailed data on cargo demands, transportation routes, and technical parameters of the existing fleet, which are adjusted to account for a battery as a primary power source. In-depth modelling of operations specifics and an advanced ship energy consumption model allow for a reliable assessment of electric ship operations with a wide range of potential applications.

We are currently developing and testing an ABM to assess the feasibility and performance of the electrified cargo shipping on the Danube River, particularly the need for ship charging infrastructure [27]. The cargo demand is based on the port statistics for the typical year, specifying the amounts of cargo to be transported in specific directions. The ABM considers four types of agents – a tug, a barge, a port, and a charging station, operating in a dynamic GIS environment. The tugs form a convoy with barges, considering the cargo demand, navigational constraints, and water depth along the route. The water depth is specified for the different regions of the Danube and changes significantly throughout the year, limiting the maximum draft of a convoy. The technical characteristics of the tugs and barges align with the typical designs commonly used in the region. However, the tug design is adjusted to account for the specifics of battery-driven operation, and the maximum attainable battery capacity is calculated. The model accounts for the resistance and energy consumption of a convoy, considering its configuration, speed, direction of movement, and the speed of the river. The energy consumption module enables tracking the state of charge for each tug. Tug agents include detailed charging-planning logic to schedule charging time and location. Figure 7 shows an estimate of accumulated electricity demand (in GWh) for the fleet at chosen charging stations.

Although the model is still a draft version, it demonstrates potential for electrifying the Danube River inland transportation system.

5. DISCUSSION

ABM is a simulation approach that captures system behavior by representing heterogeneous actors and their interactions within a defined environment. ABM has been applied across a range of domains, particularly where emergent dynamics and operational constraints limit the usefulness of aggregate or highly stylized models. The present study analyzes research applying ABMs for sustainable waterborne transport, considering ships, operations, and port infrastructure. We explicitly focus on sustainability, particularly papers studying greener waterborne technologies through improved energy efficiency, reliability, and safety. We categorize the contributions into three categories – policy-oriented applications on energy transitions in the shipping sector, applications on port infrastructure and decision-making, and simulations of freight logistics and vessel operations. These studies highlight the ability of ABMs to advance sustainability and efficiency in the corresponding applications.

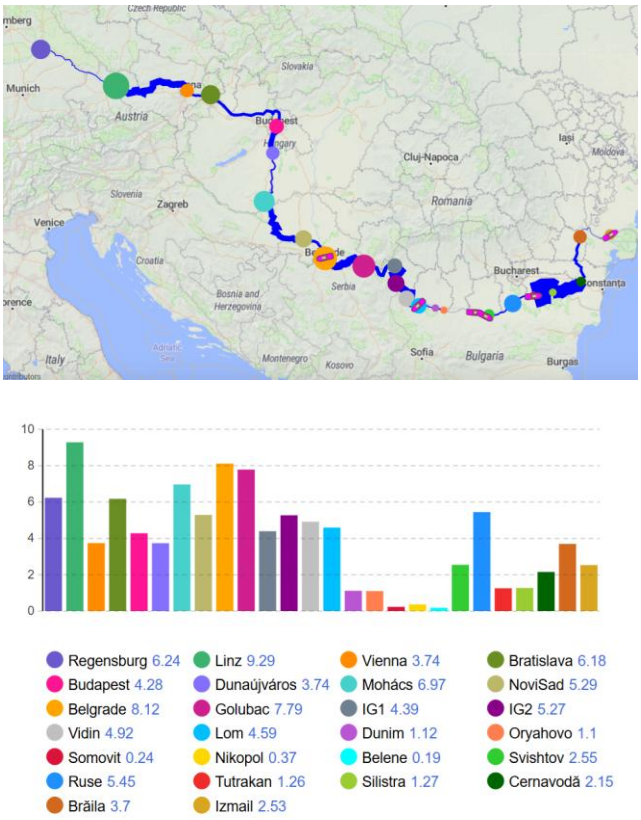


FIGURE 7: ABM SIMULATED FLEET ELECTRICITY DEMAND (GWh) FOR THE SELECTED CHARGING STATIONS [27].

The authors of the present study, along with many authors of the studied papers, have noticed a limited number of ABM applications in the waterborne sector compared to other transport modes, despite the clearly demonstrated benefits. Another observation is the ability of ABM research to successfully attract maritime stakeholders and secure their direct contributions and funding for model development, which can be challenging in academic research. This indicates that practitioners trust ABMs and their toolkit, allowing for in-depth applied research. The present study recommends wider application of ABMs to study

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complex systems within the waterborne sector, especially when aiming for a real-world impact.

6. CONCLUSION

The present study analyzed the applications of agent-based simulation in the design and analysis of green shipping and sustainable port infrastructure. The study demonstrates the significant potential of ABMs to analyze and improve the performance of complex systems with high uncertainty in the waterborne sector. Particularly, ABMs were found useful for real-world applications in polar, offshore, and inland shipping. The review shows significant trust among maritime stakeholders in ABMs and their willingness to commit time and resources to their development.

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