Simulating Growing Complexity in Maritime Traffic

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Continuous research and developments in maritime traffic often result in new levels of complexity. Technological innovation accompanied by enhanced and amended regulatory schemes result in new situations that need to be handled on board and also need to be managed from shore-based monitoring stations. Maritime Education and Training (MET) has to address these advancements, human factors, and regulatory updates, adapting them into syllabuses and course works. This also requires further enhancement of simulation-based training. In this paper we discuss increasing complexity and present investigations and results of simulation experiments focusing on the design, implementation and conduction of combined simulation exercises involving full-mission ship-handling simulation and full mission VTS-simulation. Complex scenarios provide trainees with realistic interactions between actors from different institutions within the maritime domain. This study specifically aims to answer how such simulation setups can address operational challenges and improve navigational safety under increasing traffic complexity. The experiment involved maneuvering a bulk carrier entering a harbor terminal with a pilot onboard, while receiving additional navigational assistance from a shore-based VTS station. The investigation focuses on how VTS-provided assistance enhances safety, especially when navigation aids (e.g., buoys or beacons) are unavailable due to technical or environmental challenges. The outcome of the experiment is discussed in the light of the extended capabilities and advanced opportunities of complex maritime simulation for MET and research purposes, particularly in studying human-machine interactions and operational dynamics. Main outcome and conclusion from the studies is, that the growing complexity of maritime traffic rises the need for realistic simulation scenarios. Technical developments and improvements require adequate operational procedures for smooth interaction of the different actors ensuring safe and efficient traffic flow. Simulations also provide insights to improve regulatory frameworks and human-operator training, mitigating risks from technical failures or adverse conditions.

KEYWORDS

~ Maritime transportation system
~ Simulation
~ Mixed traffic
~ VTS
~ MASS
~ Remote control

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1. INTRODUCTION

1.1. Background

Sustainable, safe, timely, and reliable transportation of goods remains a critical and growing challenge for the maritime sector. This challenge is intensified by the increasing number and size of vessels, densification of maritime traffic routes, and the rapid pace of technological and regulatory evolution within the industry. While global safety records have improved over the years in this sector—which is responsible for transporting around 90% of global trade—the risk of navigational accidents continues to be a major concern (EMSA, 2022–2024).

In parallel, the introduction of Maritime Autonomous Surface Ships (MASS) is poised to further increase the complexity of operational scenarios, both on board vessels and within shore-based monitoring and support systems such as Vessel Traffic Services (VTS). These developments present new challenges for Maritime Education and Training (MET), which must evolve to incorporate emerging technologies, revised legal frameworks, and new operational procedures into educational content and training practices. In this context, simulation-based training becomes a crucial tool to prepare maritime professionals for the growing demands of interconnected and dynamic operational environments.

1.2. Aims and Objectives

This study aims to address two interconnected objectives:

(1) to design and implement complex, realistic simulation scenarios that capture the increasing complexity of maritime navigation and communication, and
(2) to evaluate the operational effectiveness and pedagogical value of these scenarios in MET and maritime systems research.

To achieve these objectives, the study employed a methodological framework involving scenario design, full-mission experimental execution, participant observation, and post-simulation debriefings, supported by qualitative content analysis. Three full-mission simulation runs were conducted, integrating ship-handling and VTS operations under varying crew configurations. Data collection methods included video recordings, real-time observations, and structured focus group discussions, enabling triangulation of insights and strengthening the analytical depth.

The simulation exercises featured a scenario in which a container vessel enters a harbor terminal with a pilot onboard, supported by a VTS operator onshore. The scenario was complicated by the partial loss of navigational aids (e.g., missing buoys or beacons), simulating a degraded operational environment. The core experimental question was to what extent VTS navigational assistance could mitigate the impact of such disruptions, support safe navigation, and reduce cognitive load on bridge crews.

Preliminary results suggest that combined simulation scenarios significantly enhanced trainees' situational awareness and inter-institutional coordination. Participants emphasized that the interconnected simulation environment authentically replicated real-world operational challenges, particularly in terms of communication flow, decision-making under uncertainty, and shared responsibility between ship and shore actors.

These findings point to the value of complex, multi-actor simulations in preparing maritime professionals to navigate uncertainty and system disruptions. The experiment also highlighted the human operator's capacity to adapt and compensate—at least partially—for technical shortcomings when supported by effective communication and institutional collaboration.

In conclusion, the study reinforces the need to integrate high-fidelity, complex simulation environments into MET curricula. As maritime systems become increasingly digitized and interconnected, realistic training scenarios that reflect the operational intricacies of modern shipping and shore-based coordination are essential. The methodological framework and experimental design presented here offer a replicable model for both training institutions and researchers aiming to explore human–system interaction, safety culture, and adaptive capacity in future maritime operations.

2. SHIP NAVIGATION, MARITIME TRAFFIC AND COMPLEXITY

2.1. Ship Navigation

Ship navigation, carried out by the watchkeeping officer trained and educated in accordance with the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), remains central to ensuring the transportation of goods between ports under the regulatory framework of the International Maritime Organization's (IMO) SOLAS Convention.

The full-mission ship-handling simulations in this study integrate all six recognized sub-processes of navigation, offering a comprehensive platform to evaluate decision-making and human-machine interaction under realistic and controlled conditions. These sub-processes are:

- Voyage planning
- Route monitoring
- Collision avoidance
- Ship steering
- Alert management
- Condition monitoring

Each sub-process supports safe voyage execution and timely delivery of goods. These stages often involve sophisticated tools such as ECDIS, ARPA radar, and AIS, in addition to procedural knowledge.

Voyage Planning involves the utilization of nautical charts (paper or ENC), pilot books, tidal and weather information, and route optimization techniques. Tools such as route optimization algorithms and weather routing software now support dynamic planning (Psaraftis, 2019).

Route Monitoring requires real-time position verification using traditional and electronic navigation tools such as GPS, GLONASS, and radar systems. Integrated bridge systems (IBS) have enhanced monitoring precision and redundancy (Lützhöft & Dekker, 2002).

Collision Avoidance is based on situational awareness supported by radar-ARPA, AIS, ECDIS, and visual lookout. The use of AI-supported decision aids is becoming increasingly prevalent (Huang et al., 2020, Bole et al., 2014).

Ship Steering has evolved into a highly automated process, with autopilots and track control systems managing most heading and course corrections, though manual control remains essential in critical scenarios.

Alert Management addresses the processing and prioritization of warnings and alarms, which has become more complex with the proliferation of sensor and automation systems (Porathe et al., 2014).

Condition Monitoring includes monitoring of machinery and environmental conditions that indirectly influence navigational safety. Its relevance has grown with the integration of predictive maintenance and health monitoring systems on bridge systems (Lazakis et al., 2016).

2.2. Maritime Traffic – the Shore-Side Perspective of Ship Navigation

This study advances understanding of maritime traffic by simulating system interactions under stress conditions, such as the absence of navigational aids or high-traffic scenarios. Both quantitative (e.g., time to decision) and qualitative (e.g., operator perception) data were used.

Shore-based maritime traffic management shares structural similarities with onboard navigation but encompasses broader systemic responsibilities and oversight. The five main subsystems of maritime traffic identified in safety analysis literature are:

- Transport Means and Driver (Ship and Crew)
- Traffic Infrastructure (Fairways, VTS, Ports)
- Traffic Management (VTS, Maritime Safety Information)
- Administration (IMO, Flag/Port/Coastal States)
- Supporting Services and Data Systems (Hydrographic offices, e-Navigation)

These subsystems interconnect dynamically. For example, VTS operators monitor and coordinate traffic, ensuring the integration of vessels into the broader system (Praetorius et al., 2015). Interactions between ship crews and shore authorities, such as VTS centers, form part of the "socio-technical" network that ensures navigational safety.

Simulation results illustrate the impact of communication quality, infrastructure availability, and procedural clarity on the smooth functioning of these subsystems. Scenario-based training enhances the appreciation of shore-side complexity and decision-making under uncertainty (Rothblum, 2000).

The following Figure 1 provides an overview of the system of maritime traffic/maritime transportation. This general division of the components, elements and sub-systems is derived and further elaborated from a safety analysis of traffic systems of different existing transport modes (Baldauf M. et al., 2019).

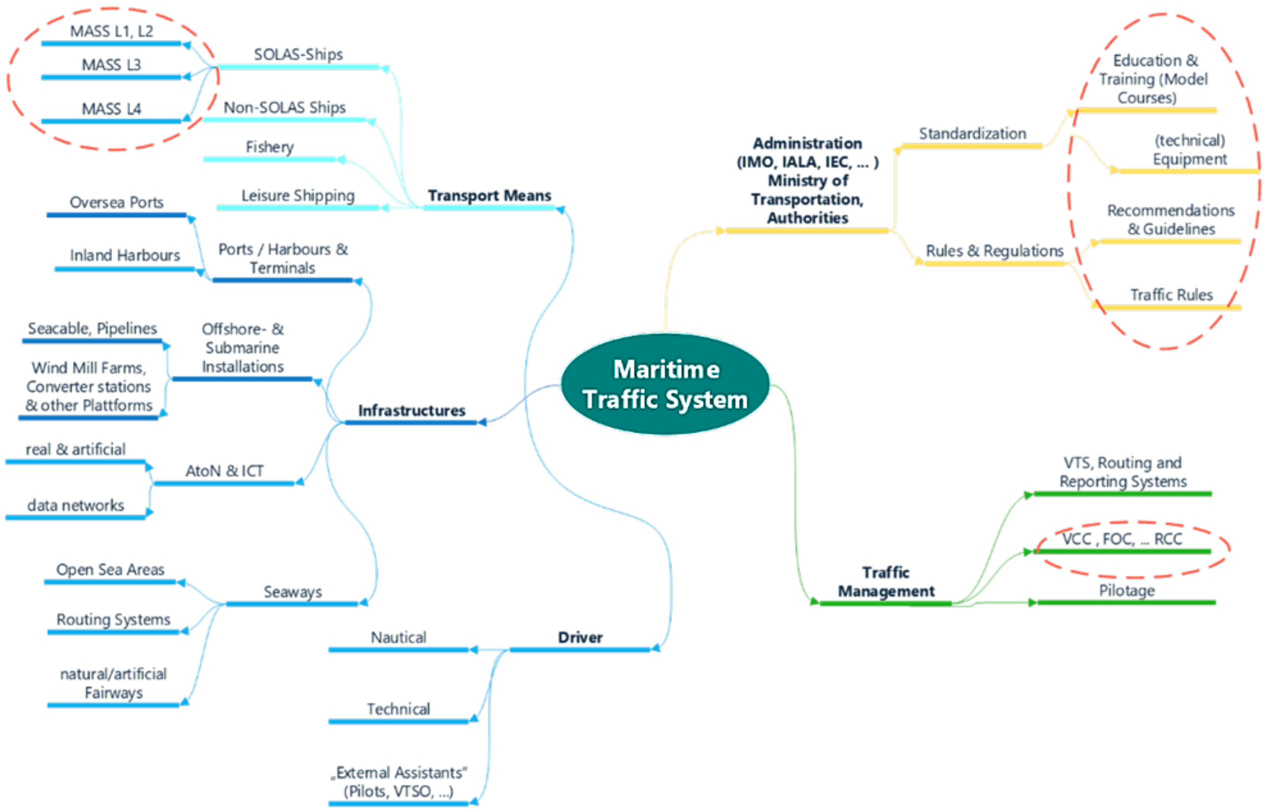

Figure 1. Elements, components and sub-systems of the Maritime Traffic System (Source: graph created by authors).

2.3. Complexity

The increasing operational complexity is analyzed using a system-of-systems approach, where interactions among ship crews, shore-based operators, and digital systems are modeled and replicated in simulation. Key complexity drivers include increased volume and heterogeneity of actors, more frequent cross-institutional communication, and integration of emergent technologies such as MASS, e-Navigation services, and decision-support systems.

Currently, there is an increasing use of the term 'complexity' in academia in regards to research in general and, specifically e.g., also in regards to maritime education and training. On the one hand, researchers arguing our world is getting more and more complex. Complexity is then often discussed in relation to "complex (navigation) systems" (e.g. Wright et al., 2016), "complex (communication) processes" (e.g. Kataria, 2016) or "complex (traffic) situations" (e.g. van Westrenen, 2019). Authors usually introduce a working definition and refer to complicated connections and relations and interactions of studied topics, objects and subjects. In regards to system's safety the handling of complex systems by human operators is studied (i.a. Mainzer, 2007 and Dörner, 1994). Increasing complexity is often explained through increasing numbers of elements or components and increasing number of dependencies, interrelations and interactions respectively. On the other hand, increasing complexity is also often reasoned by increasing number of participants in the system (increasing number of air planes, cars and lorries or ships).

In regards to the above introduced systemic approach to the maritime traffic system, we argue, that there is only little increase in the overall complexity of the maritime traffic system. There is no fundamental change in the basic structure of traffic system, even though new elements are added or about to be added (e.g. the autonomously navigating vehicles and remote operation centers). But complexity, in general, increases and becomes just only visible when considering layers below the five main sub-systems and components and elements will be identified.

There is no doubt, that there is increasing complexity when considering the deeper levels of detail of the holistic representation of the maritime traffic system including the new rules and regulations under development and to be established, the new technological developments that effect the individual operations of the sub-systems, like e.g. e-Navigation providing new communication frameworks connecting ships but also improving the connection between ships and stations ashore and allowing for the development and introduction of new maritime services. These developments are challenging the research and the maritime education and training (MET) institutes as well. MET has to address these technological developments and innovations as well as the continuous updates of the rules and regulations in the maritime domain. Consequently, research projects need to address this in their investigations (Tusher et al., 2024; Liang, 2020, Bratić et al. 2019; Mansson et al., 2017) and maritime simulations need to integrate increasing levels of complexity also to their simulation trainings (Harrington, 2024; Rostek, 2024; Baldauf et al., 2024; Pan et al., 2020, van Merriënboer et al., 2006).

Simulation scenarios were carefully designed to reflect this layered complexity by integrating varying environmental and operational parameters, such as traffic density, communication issues, and degraded navigation conditions.

Recent studies underline the growing importance of such complexity-based modeling and simulation in MET (Serani et al., 2024; Narleva & Gancheva, 2023; Hjelmervik et al., 2018).

3. MARITIME SIMULATION

3.1. Simulation in Maritime Education and Training

Simulation is not only a training tool but also a research method to study human performance in complex environments (i.a. Fan et al., 2023). In this research, simulation served both purposes: enhancing operator skills and generating empirical data for evaluating coordination, situational awareness, and procedural adherence.

Maritime simulation is to provide a realistic replica of the maritime traffic system or of parts of it relevant for specific purposes like e.g. safety studies, risk assessments, forecasts and predictions of future system's or process' status.

In maritime training and education, simulations are used to train future engineers and navigators and qualify them to sufficiently handle the real routine and emergency situations when serving at sea later on. Different types of simulations are applied to enrich training programs and provide highly realistic environment for training and education purposes of the different staff categories and training issues required by IMOs STCW convention. Moreover, simulators are also an important tool for assessment of trainees', students' performance in safety-critical situation under different conditions, like e.g. stress levels (i.a. Belev, B., et al. 2021; Sellberg, 2017).

Nowadays, the highest category of simulation of ship operation is provided through a full-mission simulator. A recently suggested classification of simulators in MET (Tusher, Munim, Nazir, 2024) mentions besides the full mission simulators, desktop-based simulators, cloud simulators and Virtual Reality simulators. The different types of simulators and simulations are specifically designed to meet the specific training aims and objectives laid down in IMO's International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) and applied to simulation exercises of dedicated courses. Simulators addressing ship handling, ship engine operation but also numerous specific purposes like e.g. cargo handling, ballast operation or safety and security trainings.

3.2. Full-Mission Ship-Handling Simulation

In our experimental design, specific complexity elements were embedded into full-mission ship-handling scenarios, such as limited visibility, system failures, and dynamic traffic. These elements were incrementally introduced to assess trainees' adaptability and resilience.

Additionally, a performance rubric based on IMO Model Courses was used for evaluating participant behavior during and after exercises (IMO, 2017; Belev et al., 2021).

Ship-handling simulation is a core part of education and training of future navigators on seagoing-vessels. All the processes introduced in the foregoing chapter needs to be integrated. A main issue of full mission simulation is to provide also replica of equipment and devices installed on a ship's navigational bridge.

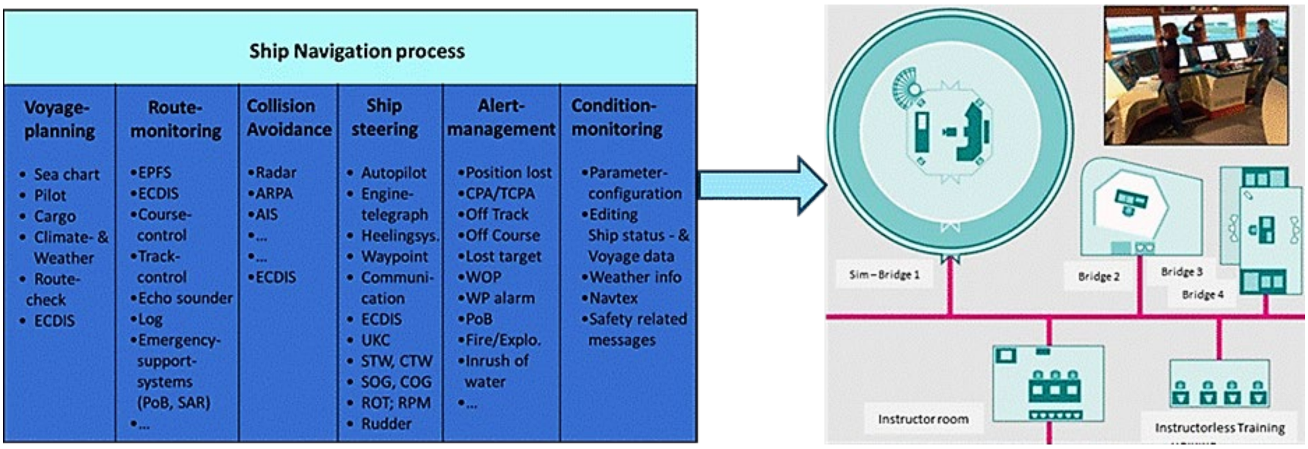

Figure 2. Integration of navigational tasks and processes into full mission ship-handling simulation (Graphics created by authors, Photo: Wismar University).

As depicted in the figure above, full mission ship-handling simulation is not only for maneuver trainings but covers the complete spectrum of navigational tasks during ship operation of a voyage including scenarios from a ship's departure from berth, transiting coastal waters including also e.g. traffic separation schemes, sailing open sea areas up to the arrival at the port of destination.

The complexity of ship operation in training exercises can be controlled through scenario design (e.g. traffic density in the training area) and variable operational events included or excluded in an exercise. For example, an instructor adds the event of an engine failure by communication as a chief officer from the instructor station to the bridge. This increase of complexity can also be done, by connecting a ship handling simulation with a full mission ship engine simulation. Complex training exercises have already been implemented in joint SES -SHS training exercises.

3.3. Full-Mission VTS-Simulation

The VTS simulation environment was synchronized with ship-handling simulations to create a seamless operational reality. This allowed for authentic assessment of joint decision-making and communication effectiveness.

Real and simulated VTS operators followed structured communication protocols of information broadcasting and navigational assistance respectively, and were evaluated based on message clarity, timing, and correctness-aligned with IALA V-103 guidelines.

As mentioned above, the maritime traffic system includes also shore-based components. When navigating in coastal waters, the Vessel Traffic Services (VTS) play a major role for organizing safe and efficient traffic flow in the monitored VTS area. Operators sending out information, navigational advice, recommendations, warnings or even instructions to all vessels in the area or to specific vessels in a developing or existing safety critical situation. Bridge teams needs to include that shore-based information into their onboard situation assessment and decision making.

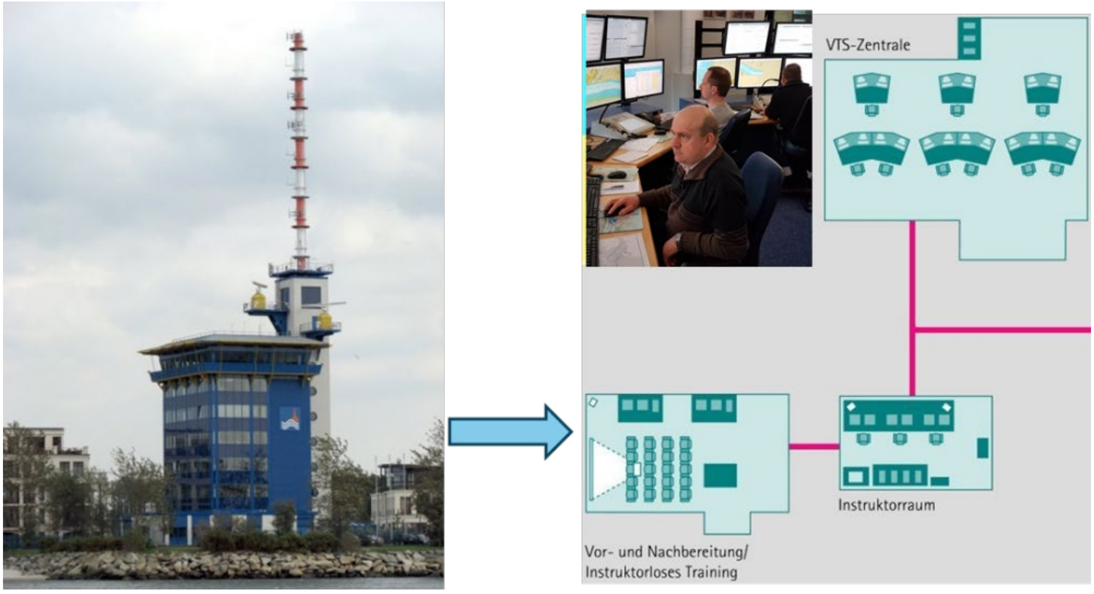

Figure 3. Integration of VTS-operation into full mission maritime simulation (Graphics created by authors, Photo: Wismar University).

Depending on the level of VTS installation and the established services of a specific VTS, there are interventions related to avoid certain critical encounter situations in narrow fairways, e.g. when an inbound large container vessel will meet another outbound vessel in a fairway bend.

Full mission VTS simulation is used for purposes of educating and training of VTS operators. VTS-operators may have nautical background and interact with vessel traffic through VHF communication basing on the assessment of their traffic image consisting of the collected environmental and traffic data available via sensors in their VTS station.

In sea areas covered by VTS surveillance, the navigators on board together with VTS operators ashore contribute to safety of navigation. In order to provide realistic scenarios for both sides it seems to be supportive to connect both simulations. It is expected that connecting full mission VTS and full ship handling simulation can improve realism.

4. CONNECTING SHIP-HANDLING AND VTS-SIMULATION

4.1. Simulation in Maritime Education and Training

The experimental setup involved three simulation runs with different role assignments to allow comparative analysis. A quasi-experimental methodology was used, supported by structured observations, video recordings, and post-simulation interviews.

Data analysis included coding of behavioral sequences, assessment of reaction times, and qualitative content analysis of debriefing transcripts using MAXQDA software.

This method allowed for capturing both processual and outcome-based metrics of team performance (Rostek et al., 2024).

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For purposes of technical and operational feasibility an experimental study was designed and carried out at the Maritime Simulation Centre in Rostock-Warnemünde. Different from the connection of numerous ship handling simulators in the European Maritime Simulator Network (Rizavanoli et al, 2015), the connection of the different two types of maritime operations - ship-handling and VTS operation were aiming at joint acting in one synchronized maritime scenario.

The technical setup of the simulator connection was realized together with manufacturers of the full mission ship-handling and the full mission VTS simulators.

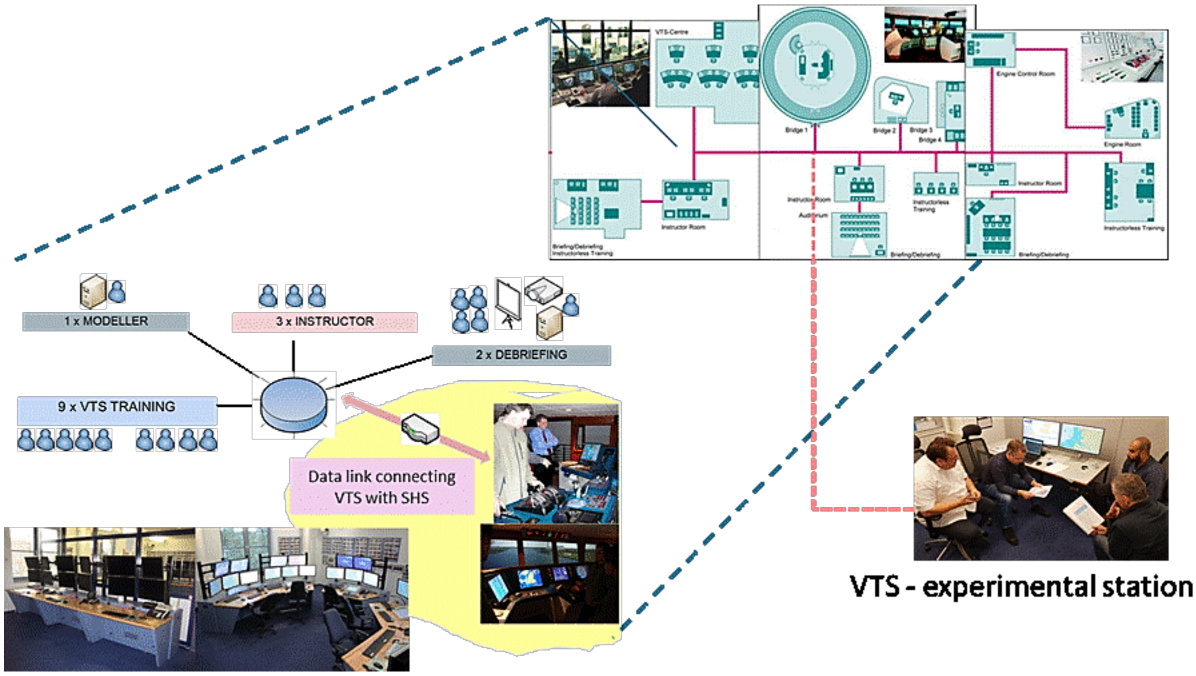

Figure 4. Connecting full mission ship-handling and full mission VTS simulation in one synchronized scenario (Graphics created by authors, Photo: Wismar University).

The technical coupling of the two systems was complemented by the development and implementation of a training scenario including traffic management aspects of a shore-based VTS supporting the bridge team of a vessel entering a harbor terminal. For the experiment the simulation model of an average bulk carrier was used and the scenario includes the passage of the linear fairway to the turning basin up to the berth.

The scenario was implemented on the ship-handling simulator serving as the master-simulator for controlling the exercise run. The bridge team consisted of an experienced pilot, an officer of the watch and a mariner served as helmsman steering the ship according to the commands given by OOW. The VTS station was manned by a chief VTS operator and a pilot providing supportive navigation assistance service (in Germany navigational assistance is provide by active pilots).

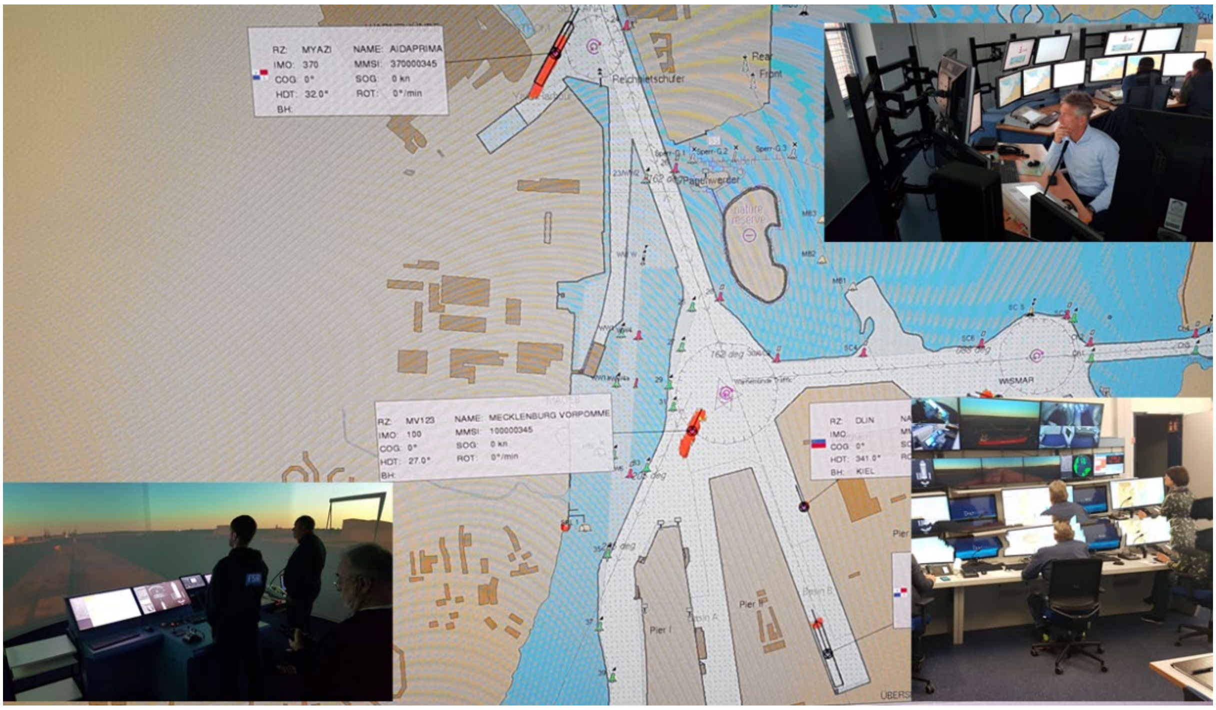

Figure 5. Combined full mission ship-handling and full mission VTS simulation in one synchronized (Graphics created by authors, Photo: Wismar University).

Figure 5 provides snapshots of the conduction of the experiment. The snapshot of the ECIDS-display is the VTS monitor station used by the pilot. In the upper right corner shows the responsible pilot at his work station in the VTS center of the VTS simulator (in the back is chief VTS operator on another screen). The snapshot bottom, left-hand-side is taken on the simulator bridge during entering the harbor area, pilot, OOW and helmsman in action. Snapshot, bottom, right-hand, depicts the chief instructor at the ship-handling simulator instructor station. Communication between the bridge team and VTS was carried out via VHF communication as originally in use (on board VHF hand-held and in VTS by a fixed HF station).

The exercise's objective for the trainees was to realize safe passage and approach to the berth with shore-based navigational assistance service. This objective was successfully achieved during a series of three simulation runs were the roles of the participants were changed. Each simulation run was recorded and concluded by a debriefing session with a focus group discussion addressing i.a. aspects of the combined simulation scenarios.

During the debriefing sessions participants very much welcomed simulation setup hang been highly realistic, "including even some technical communication lacks". Participants expressed impression complexity ("I felt he complete environment with all actors"). The participants expressed their support for joint training sessions including "exercises with active pilots – onboard and in VTS - and active VTS operators".

4.2. Key Findings

Results from the experiments indicate that realistic joint simulation of VTS and ship-handling enhances:

- Situational awareness
- Operational efficiency
- Decision accuracy
- Communication quality under pressure

Moreover, participants, in debriefing sessions and during focus group discussions, reported high perceived realism, improved trust between shore and ship actors. They anonymously highlighted a better understanding of inter-institutional collaboration requirements. These findings are consistent with previous studies on distributed simulation training (Baldauf et al., 2018; van Merriënboer et al., 2006).

5. SUMMARY AND CONCLUSION

The study provides strong evidence for the value of integrated full-mission simulations in both education and research contexts. The methodological framework developed can be replicated for further studies aiming to model complexity in the maritime domain.

By bridging ship-handling and VTS training environments, we offer a proof-of-concept for enhancing system-level thinking and collaboration skills in maritime professionals. While there are numerous samples of integrating elements of VTS operation to ship-handling simulation exercises, this study, to the best of our knowledge, for the very first time, realized complete technical and operational connection of ship-handling and VTS-simulation.

As the maritime sector undergoes digital and operational transformation, simulation-based training and research will remain pivotal in preparing human actors to operate safely in increasingly complex scenarios.

An exploration of the maritime traffic system has been carried out and the main sub-systems, components and elements have been identified. There is an increasing complexity which rises from new technological developments (new types of transport means: MASS), administrational measures (new, updated rules and regulations both on international and national level respectively) but also through new technical equipment and devices onboard and ashore. The trend of increasing complexity needs to be addressed and implemented in simulation exercises of relevant maritime education and training courses as well.

An experimental study has been carried out and demonstrated he technical and operational feasibility of connecting two different types of full mission maritime simulations, namely full mission ship-handling and full mission VTS-simulations. However, connecting simulators is an extremely challenging task for instructors. Increasing complexity requires even more diligence, careful, comprehensive and coordinated scenario design. One result from the conducted experimental simulation runs has to be concluded, that combined exercises requires even more preparation time and more human resources for coordination and conduction. On the other hand, it will support teamwork by learning and better understanding the team members' perspectives, their needs and demands.

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CONFLICT OF INTEREST

Authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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