Applications of Maritime Simulators in Industry and Research

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Abstract. Ship-bridge simulators are ideal arenas for research and innovation, hence, the use of simulators in industry and in research is ramping up. Ocean industry prospects are addressing core challenges such as food, security, energy, and climate change. The ocean holds the promise of great potential for economic growth. Appropriate tools are required for answering the questions of the emerging ocean operations. Questions related to technology development, training, safety and efficiency rise on a daily basis, where ship-bridge simulators could be the labs facilitating a wide spectrum of research experiments. This paper presents the role simulators play in maritime operations and lists various applications of ship simulators according to a literature review and nine interviews with researchers and managers in simulator centres. It also presents a case study of the current and future uses of simulators by the Norwegian Coastal Administration Pilot Service. The scope of simulator applications is wide, beside training, they are used in development of autonomous controllers and in recruitment of pilots.

An accuracy concern is identified; simulators must hold an appropriate level of accuracy to fulfil the different application objectives. The standard for Maritime Simulator System, DNVGL-ST-0033, does not recognize applications other than training. In addition, it requires no objective assessment of ship dynamics, as required by the flight simulation standard (CS-FSTD).

Keywords: Ship Simulators; remote control; accuracy requirement levels

1 Introduction

Simulations and simulators have been applied in engineering for few, even several, decades. It is the maritime domain that is transforming towards a highly digitised industry, from research, training to operations, the dependence on digital systems is increasing. On top of that, the exhaust emissions regulations are getting stricter every five years according to the Marine Environment Protection Committee of the International Maritime Organization (IMO - MEPC, 2020). This tightening of the emissions regulations is challenging all the sectors involved in the shipping industry to strive for higher efficiency. Therefore, research is a key for solving such challenges and hence, simulators are methodological enablers for future potential solutions.

The strict regulations do not only challenge ship engine and fuel type. They also challenge routing, the understanding of weather systems and environmental loading along the planned route, hence the selection of the route with minimum loading yet satisfying time and emissions constraints. The regulations also challenge the manning of ships as with reduced manning the hotel loads are reduced and thus the emissions are reduced, this brings attractiveness to the concepts of remote control and higher lev- els of autonomy in the shipping and offshore industries. This cascades into human fac- tors challenges of how teams can work together for an operation while dispersed, with parts of the team sitting in different places in the world, and so on.

In all mentioned challenges, simulations and simulators can play a role. However, because the nature of the challenges is broad, it is not clear who is using ship simulators and what they are using them for. This article aims to present an overview of the use of maritime simulators. The introduction covers background information on simulations, simulators and the industry trends of utilising them.

1.1 Simulations and Simulators

In short, simulations try to mimic real-life. The concern could be a real-life response such as in the case of fire drill, or it could be a real-life phenomenon, such as the elongation of a metal rod when heated. In the latter example, mathematical models are used to calculate the heat transfer and thus the thermal expansion of the rod. Using a computer simulation that can also take time into consideration, the phenomenon can be explored virtually on the computer. This opens the opportunity to investigate what happens if the heat source is changed, and similarly, if the type of metal is changed.

Computer simulations offer practical and convenient features. They enable running the 'virtual test' many times in fraction of the cost compared to physical testing. They allow for affordable 'testing' of extreme conditions, say, very hot temperatures that are hard to achieve in your lab's furnace. They also can be connected to other computer simulations building a mega simulation estimating multiple physical phenomena and their interactions.

Some computer simulations are designed to provide the user with a virtual experience. These are called simulators; they interact with human inputs and present the responses as they evolve on screens. Some maritime simulators are designed to provide a very immersive experience, with 360° curved projection-screens and, few of them have moving platforms. Recent generations of maritime simulators are quite immersive, the visuals are seamless high-definition projections, in a room with hardware that is identical to that found in real vessels (O. Hareide & Ostnes, 2016). Users of such simulators have fully furnished bridges including chairs, propeller levers, rudder control, radar, electronic chart displays, radio communication device, etc, as if they are on a real ship. For example, check the latest ship bridge simulator solutions of Kongsberg (K-Sim) or Wärtsilä (Transas).

As described by (Porathe, 2016), *"A ship-bridge simulator is a piece of laboratory hardware and software that simulates a ship's behaviour from the vintage point of its bridge. Often consists of a mock-up bridge (a more or less realistic bridge interior with consoles, screens, instruments and windows to the outer world) but often also a visualization, i.e. the egocentric 3D view of the surrounding world with ships, islands, and ports projected on screens outside the windows"*.

1.2 Practices and Training

Involvement of maritime simulators in both academia and industry is becoming more visible. The following are examples on national and international collaborations involving the use of simulators for advancing maritime operations:

- SFI MOVE (*https://www.ntnu.edu/move*), a Center for Research-Based Innovation for Demanding Marine Operations is using simulation-oriented approach to solve some of the pressing challenges in the offshore industry. The centre has been running for several years. This centre is an example of academy-industry collaboration for solving real-world problems using research in simulators (*SFI MOVE*, 2016).
- EU project AutoShip (*https://www.autoship-project.eu/*), where simulators will be upgraded to better support testing, commissioning, training and operations of autonomous ships (*AutoShip*, 2019).
- SFU COAST (*https://norway-coast.no/*), A Centre of Excellence in Maritime Simulator Training and Assessment envisioning the innovative potential of the best simulator practices in maritime education (*SFU COAST*, 2020).

Ship-bridge simulator-based training practices are well established in maritime education. The International Convention on Standards of Training, Certification and Watchkeeping of Seafarers (STCW) of the IMO regulates the standards of training. The main purpose of the Convention is to promote safety of life and property at sea and the protection of the marine environment to ensure that future professional mariners can operate properly and safely in their work practice, this convention emphasises on the use of simulators for both training and assessment (STCW, 1995).

For example on the use of simulators for maritime education, the set of simulator-based training courses offered by IMO, for both the novice and the experienced participants includes, but not limited to, the following simulator courses listed in **Table 1**.

Table 1. Some of the simulator-based training courses offered by the IMO (STCW, 1995).

1.	Ship simulator and bridge teamwork	2.	Liquefied petroleum gas (LPG) tanker cargo
3.	Liquefied natural gas (LNG) tanker cargo	4.	Oil tanker cargo + Ballast Handling (BH)
5.	Chemical tanker cargo + Ballast Handling (BH)	6.	Automatic Identification System (AIS)

In June 2015, after a series of EU projects from 2009, the IMO approved a "Guideline on Software Quality Assurance and Human-Centred Design (HCD) for e-Navigation". The objective of e-Navigation concept is to harmonise the collection, integration, exchange, presentation and analysis of marine information by electronic means to enhance the operations and their safety. IMO considers that e-Navigation should be user driven rather than technology driven. HCD methods require heavy involvement of seafarers and operators in the design and development process of navigation aid tools. From 2015, the IMO recommends that HCD should be used in development of new navigation equipment (MSC, 2015).

As the HCD guideline encourages the involvement of users in the design process, it also, indirectly, encourages the use of simulators in that process. The simulators can play the role of labs, for testing out the new product being under development, for measuring the user experience and user satisfaction while using the product, and for measuring the performance of the user in a virtual operation using the product. Thus, simulators can be used for testing and validation of design concepts enabling effective HCD processes.

According to DNVGL-ST-0033 (2017), the Maritime Simulator System Standard, ship simulators are classified into four groups. Class A (full mission), B (multi-task), C (limited task) and S (special task). In addition to the classes, different types of ship simulators exist, based on the type of functions they simulate, the types are listed in **Table 2**.

Table 2. Ship simulator types based on operation type (DNVGL-ST-0033, 2017).

1.	Bridge operations	2.	Machinery operations
3.	Radio communication	4.	Cargo handling
5.	Dynamic Positioning (DP)	6.	Safety and Security

7.	Vessel traffic services (VTS)	8.	Survival craft and rescue boat
9.	Offshore crane & Remotely operated vehicles (ROV)		

To sum up, simulators are not only used for training; they are also being lately used for research, design, and other applications. An overview of the use of simulators is presented herein, with focus on their use as a research tool. In addition, an overview of the opportunities and challenges associated with their usage is also presented. Hence, this article is a contribution towards answering the following questions:

- What are simulators used for?
- What are the opportunities and challenges of using them?

2 Methods

To answer the two questions above, three methods have been used. First, a literature review for relevant research that uses simulators, second, interviews with professionals and researchers in the field, and third, a case study with a relevant industry player. Details about the three methods follow.

2.1 Literature Review

The literature review is made to contribute mainly to answering the first question: "What are simulators used for?" from the research perspective. A literature search has been undertaken in the search engine "Oria" of the Norwegian University of Science and Technology (NTNU) that provides search of the university's both printed and electronic collections of internationally renowned scientific databases (and publishers) such as INSPEC (Journal of Navigation), Scopus (Elsevier, Springer, IEEE), ProQuest, TransNav and WMU. Searching for literature on the search engine Oria has been done without specifying certain databases. Only literature reporting use of navigation simulators are selected. The search criteria of the literature review are found in **Table 3**.

Table 3. Literature review search criteria

Keywords:	Ship simulator; bridge simulator; mission simulator
Publication date span:	12 years (2009 – 2021)
Material type:	Articles, journals, and conference proceedings
Filters:	Publications that do not involve use of simulators (removed)
Selection size:	80 publications (selected after applying the filter)

2.2 Interviews

Subject matter expert (SME) interviews are held to bring a variety of perspectives from both researchers and professionals in the field. A Google search was made for both academic and commercial simulator centres all over the world. Thirty-five centres were identified. A shortlist of contacts was created for interview invitations. Ten positive responses were received and actually nine interviews were performed. Five interviewees are researchers and four are managers at simulator centres. The interviewees have different backgrounds, seven of them are engineers and two have social science backgrounds. At the time, the interviewees were geographically located as follows: 5 were in Norway; 2 in Sweden; 1 in the Netherlands; and 1 in Canada. All the interviewees referred to maritime simulators in their interviews, most of them (seven out of nine) referred to full mission navigation training simulators (Class A) and the rest referred to offshore operation simulators (Class S). The interviews focused on, and started with, the interviewees' work and experience, shaping an interviewee-centred context throughout the conversation.

The interviews were designed as semi-structured interviews with open-ended questions. The duration of interviews was half-an-hour on average for each, which started with an introduction about the interviewers and their motivation for conducting this research. Inductive coding method is used for analysing the collected data. The interview questions are as follows:

1. Tell us about yourself and the field of your interest.
2. What opportunities do you think simulators provide for research (or for the industry)?
3. What challenges have you faced while using simulators for your research (or for your work)?

The inductive coding process was performed in two levels, the general themes, and the more specific items, nested under the themes. Responses were compared across all interviewees for each question at a time. Similarities among the answers were identified and were given labels for the general themes they address, such as "research and innovation facilitator" and "developing industry standards" labels for the second question about opportunities. There were three labels identified for each question. The labels describe the general themes and provide a rough description of the interview results. A higher level of detail was needed to convey the picture the interviewees painted, therefore, specific items where identified and coded. Every labelled theme then was described by several coded items. For example, in the second question (about opportunities), nested under the label "research and innovation facilitator" the following codes were given: "innovation facilitator"; "multidisciplinary"; and "proof of concept". The codes are, in most cases, self-explanatory, and provide additional level of detail to the description of the interview results. The coded items aid the labelled themes in describing the content of the interviews, and together they provide answer to usage, opportunities and challenges as presented in **Table 5**.

2.3 Case Study

The Norwegian Coastal Administration Pilot Service (NCA PS) is selected as a case study for an intensive investigation regarding their day-to-day operations and their approach to using simulators, and maritime technologies, for solving today's and tomorrow's challenges. The information is collected mainly in a webinar that is designed for the purpose of this study. The webinar was held on 19 January 2020 and was named "Learning from the Pilots". The agenda of the webinar included the following sessions as listed in **Table 4**.

Table 4. Learning from the Pilots webinar agenda

1.	Short introduction from the NCA
2.	Everyday life of a pilot
3.	"Sleipnir" platform to Haugesund operation
4.	Recruitment and simulation
5.	R&D strategies of the NCA
6.	Open discussion

The design of the webinar included long questions/answers (QA) sessions. In addition, participants, who were mainly students and researchers, were encouraged to ask. The active participation in the QA sessions was modest therefore the collection of data was mainly passive.

The interviews took place in April 2019. The literature search took place from February to April of the same year, and later the search was complemented in the beginning of 2022 to include relevant research that was published within and after the year 2019. Within the 2019, the main author participated in a research work that aims to develop a decision support tool that aids navigators in selecting the proper rudder angle for the coming turn (Dimmen et al., 2020). The decision support tool was tested in navigation simulators and the conclusion was that such a tool can help navigators in close quarter maneuvering. This conclusion motivated the author to pursue collaboration with the Pilot Service to learn about their use of technology, seeking confirmation (or rejection) of the previous conclusion. Apparently, the Pilot Service were also motivated to collaborate with researchers and eager to increase their use of technology to advance their operations. Therefore, as a first step in the collaboration, the webinar "Learning from the Pilots" was suggested. The webinar was not meant to answer a specific question, on the contrary, it was designed to convey as much as possible from the pilots' experience and challenges. Such information serves as a necessary background for the creation of different research sparks. In addition to that, supplementing this article by providing a detailed contribution on their use of simulators.

3 Results

The results are presented in this section. First, results from the literature review, second, from the interviews, and third, from the case study.

3.1 Literature Review

Starting with describing the demographics of the collected literature. It is observed that 63% of the reviewed literature belongs to the Natural Sciences, 25% belongs to the Social Sciences and the rest can be identified with both scientific branches. It is also observed that 54% of the literature is using Quantitative methods, 26% is using Qualitative methods, while the rest is using mixed methods. The literature is classified into five groups. Fig 1 includes the distribution of the literature into the five groups: Development; human factors; training; learning; and risk analysis.

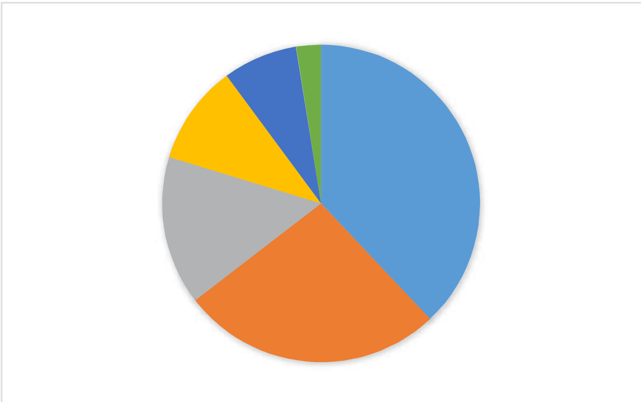

Fig. 1. Literature classification

Development

This group constitutes of 38% of the literature. This group is using the simulator as a step in the development or evaluation process. Most of this group is developing programs / algorithms that enable autonomous maneuvering, and they are using the simulator to present their development program, or to evaluate it using the human-in-the-loop concept. In the literature, the development group is not limited to products (such as programs / algorithms), it also includes development of procedures and specifications. For example, Ari et al (2013) developed a path planning algorithm that is length-optimised and feasible regarding turning radii of the given ship. They demonstrated a proof-of-concept of their algorithm using a ship simulator experiment. Varel and Sores (2015) on the other hand, developed a simulator program that is built specifically for training on ship-to-ship offloading maneuver. Their research constitutes basically of presenting the development works and final product. Hareide and Ostnes (2017) however, developed a navigation procedure that is inspired by a simulator experiment. They performed a simulator experiment with eye tracking devices. They identified efficient scan patterns and developed scan patterns for maritime navigators that maximise safety. Lastly, it is observed that virtual reality (VR) simulator development studies are emerging (Jinlong, 2019; Lauronen et al., 2020).

Human factors

This group is the second largest, constituting 27% of the literature. This group is mainly researching the human operator inside the simulator. The focus is on either the human experience, or the human performance. More than half of the literature in this group use physiological monitoring as part of their data collection methods. They measure either heart rate or brain signals to gain understanding of the workload or stress level the operator is experiencing in real-time. For example, Hontvedt (2015) introduced a study that examines the experience of professional maritime pilots in a simulator training exercise using azipod propellers to navigate in high winds. The participants reflected on their experience in debriefings. The interaction analysis performed by Hontvedt shows that simulator training has distinct advantages, however, the pilot's experienced lack of photorealism and graphical fidelity in that simulator and this could compromise the effectiveness of the training. Orlandi and Brooks (2018) also evaluated the experience of marine pilots in a berthing operation exercise. They used both qualitative data, such as the self assessment scales, the NASA TLX and the Likert scale, and quantitative data from Electrocardiography (ECG), Electroencephalography (EEG), and eye tracking. They demonstrated that they could indirectly monitor levels of mental workload as they develop over time in a demanding operation. Lastly, Nilsson et al. (2009) presented a study similar to Orlandi's, evaluating the performance of marine pilots, in two different bridges, one with more advanced instruments, and the other with less advanced technology on board. They used several data collection methods, both qualitative (questionnaires and expert opinion) and quantitative data (physiological sensors and response times). They concluded that performance is not clearly correlated with the level of technology on board, however, if mariners' experience is taken into consideration, they found a link between experienced navigators performing better in less advanced bridges and less experienced navigators performing better in more advanced bridges.

Training

15% of the literature belongs to this group. This research mainly demonstrates the potential of simulators in training of operators to achieve higher levels of safety or efficiency. Some consider training for higher energy-efficiency and lower emissions, some consider training for a specific maneuver such as the man-overboard Williamson turn, and some consider training in specific conditions such as shallow water maneuvering. For example, Benedict et al. (2014) presented their development of an innovative simulator that presents future projections of a ship's path according to current conditions. This could be classified in the development group, however, they emphasised on the value of their developed simulator in training, elaborating that it can be useful in briefing and debriefing sessions for ship handling simulator training, and that it can be used as a training tool on board ships. Jensen et al. (2018) presented a proof-of-concept of a training that is helpful in saving fuel. They stated that fuel-efficiency of ships is not merely a technical concern, they showed that awareness, knowledge, and motivation are also important parameters in fuel consumption. Lastly, Formela et al. (2015), on the other hand, used a maritime simulator to train candidates of two different man-overboard maneuvers. Their investigation concluded that the Anderson Turn is more efficient than the Williamson turn.

Learning

10% of the literature belongs to this group. A group of literature that uses the simulators in their research to focus on learning. The difference between training and learning in this context is as follows: Training describes the use of a simulator for nautical students and experienced professionals to enhance some of their relevant skills. However, learning describes the use of a simulator to understand the process of knowledge transfer (and skill transfer as well). This includes education science, the actions that contribute to learning, including the role of the instructor in briefing, debriefing, or during the exercise. For example, Hontvedt and Arnseth (2013) are researching the learning in a simulator. They are investigating the context in which students and instructors collaborate to achieve learning goals. The study shows that the collaboration and meaning making of students is an important entity to address in the design of simulator exercises. In addition, Sellberg (2018) has performed an ethnographic study to investigate the instructor role in a simulator exercise. The research shows that a continuous instructional achievement, from briefing to in-session instructions, to debriefing is highly important to facilitate learning towards a profession.

Risk analysis

A minor group that is grabbing attention in recent years, a group of literature that uses the simulators in their research to focus on safety. Statistical methods for calculating collision probabilities are common here. Some studies do reconstruction of previous accidents, such as the 'Ever Given'grounding in the Suez Canal. Others develop practices that aim for a reduction in risk, for example ship-whale strike risk. For example, Popov et al., (2021) held an investigation based on a reconstruction of the Ever-Given grounding incident in the Suez Canal in a ship simulator. Grende et al., (2019), alternatively, proposed a set of practices for reducing ship strike risk as an active whale avoidance strategy and tested its feasibility in the simulator.

Research in ship simulators is multidisciplinary. The research fields of the main authors (of the collected literature) are noted. A variety of disciplines are involved, the leading discipline herein is Ocean / Naval Engineering, followed by Teaching / Training; Safety Engineering; Computer / Control Engineering; Industrial / Civil Engineering; Psychology; Human-Computer Interaction (HCI); Social Research; Mathematics;

and others like Finance / Economics; hydrodynamics; fishery and aquatic disciplines. The distribution of the main-author-disciplines is presented in **Fig. 2**.

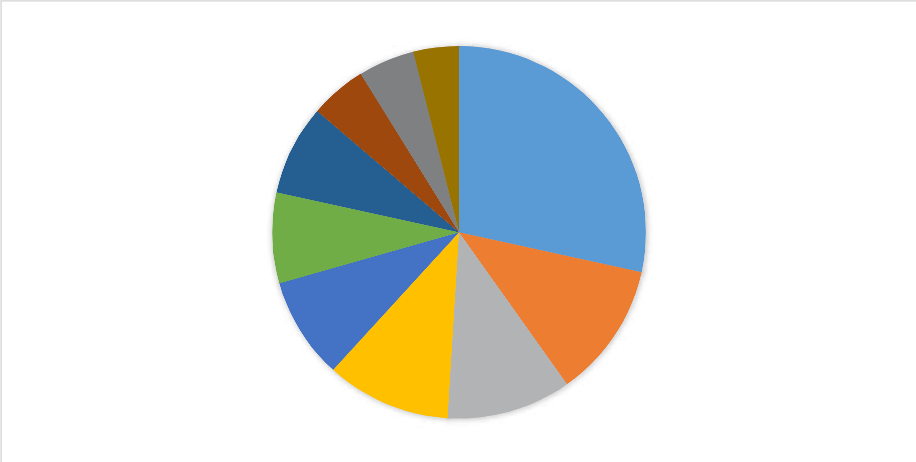

Fig. 2. Disciplines of main authors of collected literature

3.2 Interviews

The interview codes are found in Table 5. The main usage of simulators according to the interviewees is related to education and training. However, interesting applications are emerging such a sensor fusion of physiological data and the testing of technology and algorithms for enabling autonomous operations become safer than conventional ones.

The opportunities are summarised in three main points. First, simulators are facilitators of research and innovation. Second, simulators stimulate change in industry workflows. Third, simulators open new frontiers towards transforming the industry.

All researchers have agreed on the research infrastructure challenges, such as the availability of simulators and the availability of some expert helping hand to aid them throughout their experiments. While the managers mentioned issues related to cost of handling and maintaining simulator facilities. Interviewees using offshore operations (Class S) simulators were more innovation-oriented in their answers focusing on simulators' role in development of products and development of industry workflows. Elaboration on the results follows in the discussions section.

Table 5. Interview codes

Q1: Usage	Q2: Opportunities	Q3: Challenges
Education and training • Performing demanding tasks • Individual and group training • Training novice and professional • Leadership training • Joint situational awareness • Enhancing safety and efficiency	**Research and innovation facilitator** • Innovation facilitator • Multidisciplinary • Flexible scenarios • Connect simulators together • Autonomous docking • Complete control of situation • Proof of concept • Huge savings • Human factors: teams/genders/cultures • Training of algorithms/people/procedures • Observing the experts	**Research infrastructure challenges** • Availability of simulators • Availability of participants • Availability of technical support • Availability of maritime research partner • Data management • Availability of hardware
Reseach in education • Learning curves • Research "learning" • Instructor role	**Developing industry standards** • Development of design methods • Validation of new methods	**Simulator being just a simulator** • Limited setup flexibility • Duration of simulation • Location of simulation • Simulator maintenance cost • Bugs and shutdowns
Research in technology • Collecting physiological data • Testing interaction • Data driven models • Human/hardware in the loop	**New frontiers** • Harsh environments • Autonomous vessels • Testing rare scenarios	**Technology readiness** • Sensor technology • Validity and reliability • Physics in co-simulation

3.3 Case Study

This section lists simulator applications according to the Norwegian Coastal Administration Pilot Service (NCA PS), followed by a bullet-point highlight of their research and development strategy.

Simulator applications

Five simulator applications according to the NCA PS are listed below:

I. During the preparations of the pilotage of Sleipner platform into Haugesund port; that is a maneuver with a huge platform and tiny margins. Part of the training for this operation took place at Heerema simulator centre.

II. In the recruitment process, the NCA shifted their focus towards people skills, learning ability and the ability to acquire knowledge. Since 2018 the NCA is using, among other tools, simulators at NTNU to achieve this objective. They use general mental abilities (GMA) tests, personality tests, ability and skill tests, stress tests, structured job interviews and simulator exercises. In the simulator exercises, factors such as blackouts, lack of GPS, gyro-errors, and ocean currents are inserted into the scenarios to make them as challenging as they can possibly get in real-life. The NCA is using a panel of pilots, pilot director staff members, HR consultant, and the leader of the pilot district, which is a widely exposed assessment group, structured assessment forms describing what to evaluate and occasional pauses are scheduled to adjust the candidates and give them feedback and see if they can learn from their earlier mistakes. Correspondence between previous tests and real time impressions are checked. A lot is revealed about the candidates, and simulators create a suitable environment for research. The NCA's practical experience with simulators for the final cut assessments is that simulators are well suited; for they unveil the candidates' strengths and weaknesses. Still, the NCA would need to have objective ways of measuring candidates' conditions (pulse/stress/forms) and assessing candidates' overall performance.

III. Simulators are used for safety critical port operations. Ports are the same, ships are increasing in size, weather is sometimes harsh, simulators can be used to test external limits to operations that may have previously been deemed too risky. Simulator port studies consist of**:**
   - Risk assessments: define a given risk for a vessel on arrival / departure under various meteorological conditions.
   - Mooring analysis: identifies mooring opportunities towards the harbour, the risk associated with this and the outer meteorological limits of the mooring. For ex: "*can MS lona at 340 m length berth in Stavanger with 35 knots wind?*"

IV. Simulators are used for operational training (demanding operations). Can be a general training or a specific training. Can focus on technical skills, coordination, cooperation, leadership, and/or communication. Can be general training such as ship handling, tug courses, VTS, and bridge resource management (BRM) courses. Can be specific training on predefined assignments such as the entering and leaving of Nexans in Halden. Can be training for distribution of learning across the organisation, organisational culture, and safety culture.

V. Ship handling training through virtual reality simulators. The NCA is developing a VR simulator with adaptable ship models for pilotage training in advance of the real operation. Beside that, this tool can be used for BRM, teamwork and risk assessment studies.

Key areas for NCA's R&D strategy.

- Bridge Resource Management (BRM)
- Pilot – Vessel Traffic Service (VTS) co-operation
- E-Navigation (enhanced navigation such as decision support using digitalization)
- Sensors and sensor technology
- Safety culture

- Recruitment and leadership

4 Discussions

The results from the three data collection methods are merged into a mind-map showing the extent of the usage of maritime simulators. The applications are categorised in 6 categories as such:

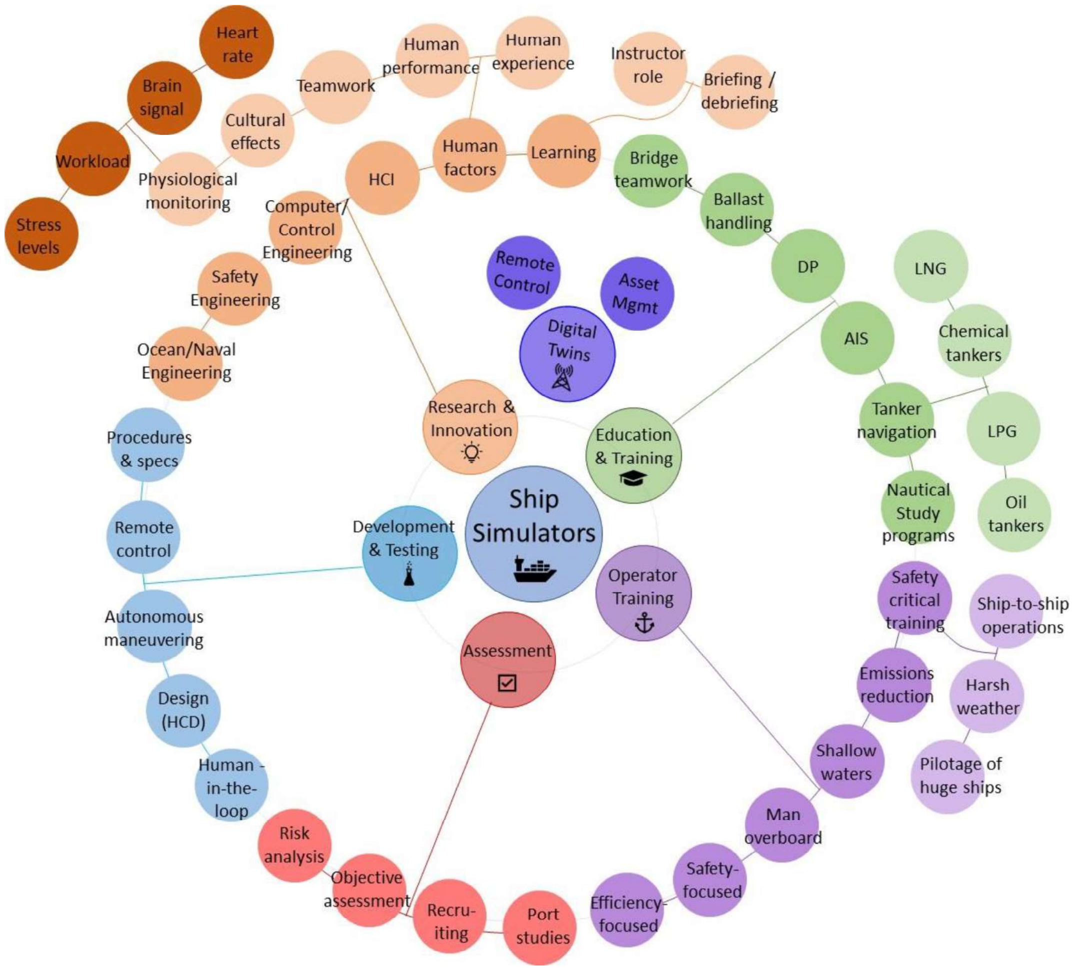

Fig. 3. Simulator applications mindmap.

i. Education and training
ii. Operator training

iii. Assessment
iv. Development and testing
v. Research and innovation
vi. Digital twins

Where, AIS: Automatic identification system,
and, DP: Dynamic positioning,
HCD: Human centred design,
HCI: Human-computer interaction,
LNG: Liquified natural gas,
LPG: Liquified petroleum gas

Fig.3 shows that simulators are not only used for mari- time education. Simulators are becoming more vital in industry processes such as de- sign and operations. Simulators are multidisciplinary labs that can gather expertise with a variety of roles for achieving specific purposes challenging the harsh and remote off- shore environment. The sixth category (Digital twins) is an emerging umbrella of ap- plications that naturally can be performed in a simulator. In Digital twins, the ships on the screens are representing real assets in operation. Simulators can be used to manage these assets, or as could be expected, to remotely control them.

One of the interviewees described the accuracy of physics in simulations as a challenge. Connecting this point with the aggregated range of applications. It is identified that some applications require higher functional fidelity than others. Functional fidelity represents the accuracy of the physics of ship movement in water (Hontvedt & Øvergård, 2020). For example, the application of training of nautical students probably requires a more relaxed functional fidelity than that of the application of pilot recruitment assessments. Such a challenge is raising awareness of the maritime simulator standard on accuracy requirements, which is elaborated in Section 4.3.

4.1 Simulator's Role in Our Lives

Simulators are no longer mainly used for nautical education. The offshore industries are rapidly growing with examples such as bottom-fixed wind turbines, floating wind farms, fish farming, subsea completions, bridges, tunnels, and the ocean surveying industry. Together with growth of the quantity and quality of offshore operations, the challenges imposed by distance-to-shore, environmental loads, weather, and the IMO energy efficiency regulations force the industry to evolve into a safer and more efficient one. Therefore, our methods for collaboration, design, and training have to evolve. There is a need for a development medium and simulators naturally fill this gap, and give us the potential to sit in the same room with our various roles from management, operations, nautical, designers and researchers.

In this sense, simulators can be viewed as enablers of operations that are usually deemed as impossible. We foresee that the demand for simulators will continue to rise.

Simulators will help us design and build the ships of tomorrow. They will help us remotely control surveying robots going as deep as the deepest point of the ocean goes. Simulators will help us enhance the way we install floating wind turbines. Simulators will help us enhance port infrastructure and waterways. They will help us in pilotage of huge containerships with autonomous tugboats. Simulators will train us to work together, with our different roles, different languages, and cultures. Likewise, simulators will help us manage our risks and achieve more with what we have.

4.2 Opportunities and Challenges

Simulators offer proof of concept capability to innovations in ship-bridge design, port design, and research ideas. Simulators are a haven for human factors and sociocultural diversity research. Nevertheless, the research and development of autonomous and remotely controlled vessels will depend largely on simulator experiments.

Main advantages of simulators are compressed into the following features: simulators enable human-in-the-loop and hardware-in-the-loop investigations. They allow investigations in harsh conditions, and in all kinds of weather, including winds, waves, and ocean currents. Simulators save time, they enable us to perform trials on a specific route relieving us from the duty of sailing back. Finally, simulators enable us to control variables, such as weather, that are impossible to control in real-world experiments.

Besides limitless opportunities, ship simulators have challenges of their own, some challenges are philosophical, linked to the fact that simulators *mimic* real-world, but they are not so. Other challenges are physical, related to the fact that ship simulators are not available upon demand, they are scarce and usually fully booked. The rest of the challenges are technological, even though advanced simulators provide a seamless performance that cannot be parted from reality, simulators do, occasionally, glitch, requiring updates and maintenance. In addition, the immersive feeling of a top notch navigation simulator does not imply realistic physics.

4.3 Simulator Accuracy Concerns

The broad scope of ship simulators' applications is raising the validity concern. In this paper, the concern is limited to hydrodynamic model fidelity that governs ship maneuvering behaviour in a simulator. Noting that most ship simulators included in this study are developed for education and training purposes, nevertheless, they are ac- tually used for a much wider application. In the maritime industry, ship models undergo subjective validations. Subjective testing is basically the acceptance of an experienced officer, which is an important consideration. However, the introduction of objective testing, in the certification of simulators and / or ship models is crucial. Objective testing is a quantitative assessment based on comparison with validation data. Validation data is derived from full-scale sea trials done with the specific ship the model is replicating, or from free-running basin trials (model tests).

The airline industry, according to the Certification Specifications for Aeroplane Flight Simulation Training Devices (CS-FSTD) of the European Aviation Safety Agency (EASA), is addressing accuracy concerns (CS-FSTD, 2018). The concerns are addressed within the certification specifications. Qualification guidelines include objective testing in addition to pilot acceptance (subjective testing) and functional testing. The objective testing covers a range of plane behaviour details including flight dynamics, the response of the aeroplane to drag, thrust, attitude, altitude, temperature, centre-of-gravity, and etc. Among others, test categories also cover ground effects, wind shear effects, simulator computer capacity, aerodynamic modelling, stall characteristics, icing, mass properties and others.

Taking the full flight simulators (FFS) as an example, they are classified in four levels, A, B, C, and D (level D has highest functionality) according to their functionalities and match against validation data given defined tolerances. The maritime industry should account for such certification specifications for ship models taking into consideration maneuvering behaviour in calm water and environmental effects.

In the maritime industry, a DNV Standard exists for Maritime Simulator Systems that gives requirements of the performance of maritime simulator systems. The objective of the standard is to provide appropriate levels of physics and behaviour realism in accordance with training and assessment objectives (DNVGL-ST-0033, 2017). The standard recognizes different types of simulators such as crisis management, oil spill, mobile offshore unit, high-speed craft, fishery and other simulator types, but does not provide certification specifications per type. Type specific requirements can be dealt with separately using compliance statements.

This standard lists requirements related to behavioural realism, physical realism, operating environment, and dynamic behaviour. Few of the general requirements specified therein relevant to ship dynamics are summarised as: Own ship shall be based on a 6 degree-of-freedom mathematical model. The model shall realistically simulate own ship hydrodynamics in open water conditions including effects of winds, waves, tidal stream and currents. Class A simulators, in addition, are required to simulate realistically own ship hydrodynamics in restricted waterways including shallow water effects, bank effects, interaction with other ships and direct, counter, and sheer currents.

An appendix is added to the standard version of 2017 for the documentation specifications of mathematical and hydrodynamic models used in simulator systems. This includes the documentation of speed data, tactical diameter, and crash stop distance. The mentioned data shall be modelled, documented and verified.

It is obvious that the standard aims to provide ‘fit-for-purpose’ simulators and touches upon ship behaviour and hydrodynamic modelling. Despite that, it is also observed that there are two main shortcomings of such a standard. First, the standard recognizes only education and training types of simulator applications. The other application categories, presented in fig. 3, are neglected. Second, the standard requires the verification of maneuverability indicators such as full speed and tactical diameter. This set of indicators is not elaborate enough to describe maneuverability of a ship and does not comply with the indicators specified in the maneuverability standards (IMO MSC.137(76), 2002). In addition, the standard does not specify how to verify the given indicators. The verification is indeed a challenge and it lies in the core of the matter of the objective of such a simulator standard: "providing appropriate level of physics and behaviour realism…"

4.4 Limitations

The three data collection methods used herein provide a solid base to answer the research questions, mainly on the application of simulators in the maritime industry. However, the used methods are not absolutely comprehensive in this endeavour reasons such as the following:

- The literature review provides insight about simulator application in the last 12 years, however, it is blind on the evolution of the use of simulators since they were first introduced in both academia and industry.
- Interviews may suffer from a selection bias because all the interviewees except one are from North-European countries. The representation of Asia, Africa, the Americas, and Australia is overlooked. In addition, other type of users exist that were not considered in the selection, such as nautical teachers and simulator developers.
- The case study provides a rich, relevant and up-to-date perspective that cannot be found in the literature, however, this is an eye-opener that there exist other perspectives not covered herein such as: Navy; Oil and gas industry and emerging blue economy industries.

4.5 Contribution

The combination of the three methods shows great potential in the use of simulators for both research and industry. The literature review provided examples from the research domain. The interviews provided deeper insight into experts' experiences, and the case study supplemented the results with relevant and up-to-date operational input. The primary contribution of this work is answering the research questions connected with the use, opportunities and challenges associated with maritime simulators. The primary contribution can be mainly manifested in the overview of application presented in **Fig. 3**.

The additional contribution is the identification of the accuracy concern. Some applications require high functional fidelity, meaning, high accuracy in ship dynamics during maneuvering. For example, assessment applications such as port studies, recruitment, and risk analysis. Outcomes of such simulator applications could drive decisions with considerable ramifications. In such cases, the simulator application could leap beyond the scope of its intended application. Raising an alarm on the ship dynamics fidelity, and after reviewing the maritime simulation standard, a gap in the requirements for ship dynamics evaluation was identified. A contrast is made with aeroplane simulator standards to confirm the relevance of the gap. This gap is clarified in Section 4.3.

5 Conclusions

5.1 Main findings

Ocean economy is addressing vital challenges such as food security, energy security and climate change. Emerging ocean operations face a multitude of challenges where simulators can serve as multidisciplinary laboratories for research, development, and innovation.

It is observed from the literature review that simulators invite researchers from various academic backgrounds, meaning that simulators are used for investigations concerning different perspectives such as human factors, development, training, learning and others. It is also observed that there is a lack of research contribution from the academic field of nautical science, probably because nautical students tend to fulfil the basic levels and proceed with operational careers instead of academic or research careers.

The interviewees agree on the potential simulators have in research, innovation and in changing industry workflows towards more inclusive design procedures and more collaborative operational mindsets.

Norwegian Coastal Administration Pilot Service uses ship simulators in recruitment, training, and innovation. Among other challenges, they face operational challenges, such as ships becoming larger, and waterways remain the same. They also have technological, interpersonal, fatigue-related, and practical challenges. NCA pilot service sees simulators as fit to contribute to training to the various kinds of challenges.

Simulators are used for applications beyond education and training. They are used for operator training, assessments, development and testing, and research and innovation. Some applications require higher fidelity in the ship dynamics than others. An accuracy concern in the maritime simulator standard is identified, raising awareness of the fitness of simulators for some of the high accuracy demanding applications.

5.2 Future work

- Develop a more comprehensive maritime simulator accuracy standard and specifications for validating simulators against these standards.

- Investigate the use of state-of-the-art Virtual Reality simulators in the maritime industry.

6 Acknowledgements

Thanks to my colleagues and the time they shared with me in good discussions. Thanks to the interviewees for accepting my invitations and taking part in this research. Thanks to the Pilot services of the Norwegian Coastal Administration for their cooperation.

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