Opportunities and Challenges in Using Ship-Bridge Simulators in Maritime Research

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Abstract - **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 daily basis. Ship-bridge simulators are ideal arenas for research and innovation. Simulators are used in maritime contexts, mainly in education and training. However not much is published regarding the use of simulators in maritime research. This paper presents a literature review of the use of simulators in maritime research in the recent years. Additionally, it highlights the opportunities and challenges of using simulators in the maritime industry according to interviews held with academics and professionals in the field, in Norway and abroad.**

Keywords
Ship simulators, research, opportunities and challenges, training, the future of shipping.

INTRODUCTION

What is a simulation? What is a simulator?

Replication, duplication and projection of reality are three faces of simulation. Role-play, maps, and computers are possible tools for running simulations. Computer simulations are powerful tools to study complex systems and have wide variety of applications in engineering, science, medicine, economics and social sciences. A computer simulation, in its narrowest sense, is a computer program that follows step-by-step instructions to approximate the state of the system being described by the instructions. The algorithm takes as input the initial values (the values of all of its variables at time t equals to zero). Then it calculates the system's state (the variables of interest) at the first time step.

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From the values of the state at the first time step it calculates the state at the second time step, and so on the computer simulation progresses the calculations with time. The results of the computer simulation can be visualized and compared to results obtained from a scientific instrument that measures the system's state.

According to Winsberg (2003): "Successful simulation studies do more than compute numbers. They make use of a variety of techniques to draw inferences from these numbers. Simulations make creative use of calculational techniques that can only be motivated extra-mathematically and extra-theoretically. As such, unlike simple computations that can be carried out on a computer, the results of simulations are not automatically reliable. Much effort and expertise goes into deciding which simulation results are reliable and which are not."

Simulations are generally used for estimation of system states (prediction of data that we do not have) or generating understanding of data that we do already have. In the case of ship motion, the simulation accounts for hydrodynamics seakeeping and maneuvering theories in finding the progress of motions in the desired degrees of freedom. Mathematical equations based on those theories are at the core of the simulation. It also accounts for environmental loads as stochastic processes that keep on changing with time. The loads from winds, waves and currents are fed, at every time step, into the mathematical equations and influence the resultant force. The force that affects the direction and magnitude of the motion of the ship. Still, the motion of the ship can be controlled by, for example, rudder and thruster human inputs. Such control inputs can also be incorporated, otherwise be set as predefined states, depending on the goals and objectives of the simulation.

A computer simulation is normally run on a desktop computer and the results are processed and visualized, mainly in graphs, after the calculation is over. Whereas, a simulator is a real time computer simulation that looks and feels like reality, it is "a piece of equipment that is designed to represent real conditions, for example in an aircraft or spacecraft: people learning to fly often practice on a flight simulator." (Cambridge University Press, 2018).

Simulator is interactive, with human in the loop, such as in a flight simulator, sailing simulator or a driving simulator. It is "a device that enables the operator to reproduce or represent under test conditions phenomena likely to occur in actual performance" (Merriam-Webster, 2016).

Industry trends regarding the use of simulators

Use of simulators, either for entertainment or for training, is increasing. Nowadays there are off-the-shelf bicycle simulators and golf simulators for customers that want to practice at home. Apart from personal-use simulators, the use of simulators in the industry is expanding. The healthcare industry is using medical simulators to teach therapeutic and diagnostic procedures. The automotive industry is using truck simulators to provide beginners adequate training. CARLA is an open source simulator for autonomous driving research to support development, training and validation of autonomous urban driving systems (Dosovitskiy *et al*, 2017). The racing industry is using racing simulators to train professional racers maintain their skill and sharpness. The chemical industry is using operator-training simulators to create a safe and realistic virtual environment to train engineers for safer operations in process plants. In the space industry, shuttle grounds operations simulator is used to debug and verify the functionality of space application software of the international space station. Ending the examples with the maritime industry, ship-bridge simulators, remotely operated underwater vehicles (ROV) simulators and crane simulators are used together for advanced offshore operations planning.

Trends regarding use of simulators in training and education

Ship-bridge simulator-based training practice is well established in maritime education. The International Convention on Standards of Training, Certification and Watchkeeping of Seafarers (STCW) of the International Maritime Organization (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 emphasizes on the use of simulators for both training and assessment.

The set of simulator-based training courses offered by IMO, for both the novice and the experienced participants includes:

- *Ship simulator and bridge teamwork course;*
- *Liquefied petroleum gas (LPG) tanker cargo & ballast handling simulator course;*
- *Liquefied natural gas (LNG) tanker cargo & ballast handling simulator course;*
- *Chemical tanker cargo & ballast handling simulator course;*
- *Oil tanker cargo and ballast handling simulator course;*
- *Automatic Identification System (AIS) course; and*
- *Train the simulator trainer and assessor course.*

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 harmonize 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 involvements 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 (IMO, 2015).

Maritime simulators are classified into four classes based on their capabilities. Class A (full mission); Class B (multi-task); Class C (limited task); and Class S (special task) is used when the performance is defined on a case by case basis (Det Norske Veritas, 2011). Different types of maritime simulators exist, related to the operation they replicate, for example:

- Bridge operation simulator;
- Machinery operation simulator;
- Radio communication simulation;
- Cargo handling simulator;
- Dynamic positioning (DP) simulator;
- Safety and security simulator;
- Vessel traffic services (VTS) simulator;
- Survival craft and rescue boat operations simulator;
- Offshore crane operation simulator; and
- Remotely operated vehicles (ROV) operation simulator.

This article is about the use of ship-bridge simulators in research, this includes simulator Classes A & B, and bridge operation and dynamic positioning simulator types. Other names are also used to describe them such as full-mission simulators and ship handling simulators. In this article, the simulators of interest are ship-bridge simulators. From now on the term "simulators" is used to refer to ship-bridge simulators. As described by Porathe (2016) "A ship-bridge simulator is a piece of laboratory hardware and software that simulates a ship's behavior 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".

While lately, the demand in using simulators is increasing and the purposes of using simulators are branching into specific niches. Simulators are not only used for training, they are also being lately used in research. This paper tries to answer the following questions:

1. What are simulators currently used for in research?
2. What are the opportunities of using simulators in research?
3. What are the challenges of using simulators in research?

METHODOLOGY

In order to answer the three questions above, two main methods have been used. First is a literature review for relevant research that uses simulators, second is interviews with professionals and researchers in the field. Details about the two methods follow.

Method I – The literature review is made to contribute mainly in answering the first question: "What are simulators used for in research?" A literature search 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. Search criteria of the literature review are as follows:

Table 1: Literature review search criteria

Keywords:	Ship simulator; bridge simulator; mission simulator
Publication date:	Last 10 years
Material type:	Articles and journals
Other filters:	The publications that do not involve use of simulator are filtered out
Number:	50 publications

Method II – Interviews were 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 centers all over the world. Thirty-five centers were found. A shortlist of contacts for interview invitations was created that includes the following three groups:

Group i. Six internal researchers (employed by NTNU) that have performed experiments in simulators.

Group ii. Sixteen external researches (employed by other institutions around the world) that were first authors of publications found in the literature review.

Group iii. Twelve managers at research centers.

The shortlisted people were invited to interviews. Ten positive responses were received and actually nine interviews were performed: four from the first group; one from the second group; and four from the third group. The interview questions were the same for all of the interviewed persons. A little bit of customization was included in the introduction of the interviews to fit with every person's background and current works. The interview questions are:

Question i. Tell us about yourself and the field of your interest.

Question ii. What opportunities do you think simulators provide for research (/ or for the industry)?

Question iii. What challenges you faced during using simulators for your research (/or for your work)?

The general semi-structured open-ended questions helped in outlining the interview conversation. They were half-an-hour interviews that started with an introduction about the authors of this article and their motivation for writing it. This paper utilized inductive coding method for analyzing data from interviews.

LITERATURE REVIEW

Fifty publication were found based on the search criteria. The publications are classified into three categories. The first category is "Simulator Facility" and this concerns publications that focus on the simulator facility itself, they provide proposals of software and hardware developments, including algorithms and models. The second category is "Experimental Practice" and this concerns publications that provide knowledge about the practice of performing experiment in the simulator, this includes instructor roles, hierarchies and social structures. The third category is "Training and Evaluation" and this concerns publications that report on methods for performance monitoring of navigators, including evaluations of teamwork and training for specific operations. The Venn diagram of the classification is shown in Figure 1.

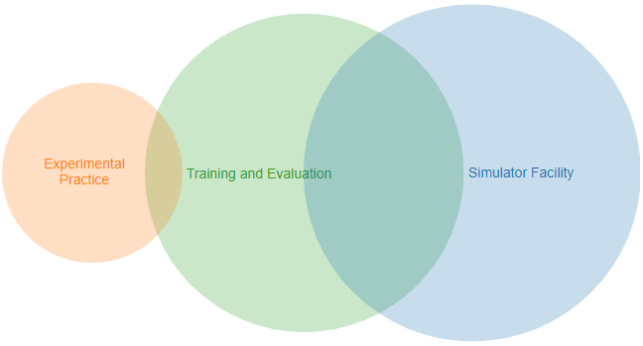

Figure 1: Venn diagram of the literature classification. Created by the online tool https://www.meta-chart.com/venn

The publications of the *Simulator Facility* category are split into five sub-classifications as presented in Table 2. The table provides a sample of publication names and lists the remaining references for each sub-classification. Table 2 is found in the Appendix.

The *Evaluation of technology* sub-classification includes publications that investigates technologies such as visual system; advanced decision support systems; direct gesture interaction methods; and accuracy of hydrodynamic methods.

The *Software for autonomous capability* sub-classification includes publications that propose algorithms and models for autonomous maneuvering; intelligent target ships maneuvering; communication and intention exchange; and safety quantification. One publication presents the capability of generating real-time objects in a simulator based on Automatic Identification System (AIS) data (Last, Kroker, & Linsen, 2017).

The *Software for fuel and emissions* sub-classification includes publications that investigate the relationship between maneuvering and fuel efficiency or emissions. Such research do not only provide knowledge, also provides models that can be incorporated in a simulator to extend its usage.

The *Software for human evaluation* sub-classification is a subset of the *Training and Evaluation* category. It includes methods and algorithms for quantifying human interactions; performance; non-technical skills and mental workload.

The *Software for specific operation* sub-classification includes publications that presents software additions to simulators to enable simulations of specific operations such as icebreaker escort; restricted waters maneuvering; ship-to-ship lightering and shallow waters maneuvering with attention to ship squat.

The publications of the *Experimental Practice* category are split into two sub-classifications as presented in Table 3. Table 3 is found in the Appendix.

The *Safety training* sub-classification includes publications presenting simulator experimental practices for ship Bridge Resource Management training; simulating marine collisions leading to a safer operating future, and benefits for safety training and investigation.

The *Pedagogical approach* sub-classification includes publications that provide analysis and assessment of the training activity. They focus on the learning component and the actions of instructors.

The publications of the *Training and Evaluation* category are split into three sub-classifications as presented in Table 4. Table 4 is found in the Appendix.

The *Evaluation of training technology* sub-classification includes publications that examine the effect of technology advancements on human performance.

The *Performance evaluation* sub-classification includes publications that study the human performance. Most of them study the human performance quantitatively using physiological measurements. Quantification efforts of the following are apparent: workload; human interactions; mental stress and strain; and teamwork.

The *Technology on Training* sub-classification includes innovative methods for training for specific operations. Training such as emergency unberthing without tug assistance and training for energy-efficient maneuvering. Additionally, it includes methods for quantifying training evaluation, such as the proposal of an evaluation index for berthing operations.

The literature shows two main paths and one emerging path of simulator research. The first main path evolves around the capability of the simulator facility. On the one hand, investigating the current capabilities, such as the accuracy of hydrodynamic models. On the other hand, developing models that enable new capabilities such as simulating ship-to-ship lightering operations. The second main path evolves around the use of simulators for training and evaluation. This path investigates and utilizes technology for training. In addition, this path focuses on quantification, providing methods for performance evaluation in a quantitative manner. Finally, the emerging path is investigating “how to make the most of simulator training by understanding the practice?” this path mainly concerns the simulator

instructors. Next section is the presentation of the second method, the interviews.

INTERVIEWS

Nine interviews were held. Conversations about usage, opportunities and challenges of simulators were coded and analyzed. The interview findings are listed in Table 5. The next section, Discussions, includes two parts, the analysis of the interviews, and the discussions based on the two methods. Table 5 is found in the Appendix.

The interviewees have different backgrounds, seven of them have engineering background and two have social science background. The main usage of simulators according to the interviews is related to education and training. However, interesting applications are emerging such as sensor fusion of physiological data and testing technology and algorithms towards autonomous operations.

The opportunities are summarized 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 the researchers have agreed on the research infrastructure challenges. Such as the availability of simulators and 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. Analysis, interpretations and discussions follow in the next section.

DISCUSSIONS

In the light of data from both the literature review and the interviews, the three areas (usage, opportunities and challenges) are discussed in this section. The literature review data provided relevant and up-to-date knowledge regarding research using simulators. The authors have very different backgrounds, in fact, the majority of researchers are not from nautical science disciplines. However, in interviews, researchers emphasized the challenge of needing some expert help to aid them throughout the experiments. Since the nautical science education in not taking precedence over the research in ship-bridge simulators, then a gap and a need in maritime research activity is identified. Filling such a gap will shape the future of shipping. Especially that simulators are embracing multi-disciplinarity and bringing human and technology in the loop. Domain education and expertise are worth to be brought in the loop as well.

Usage

It is promising to see this spectrum of research disciplines running simulator experiments in the last ten years. However, the use of simulators in research is limited to researchers with access to simulators. This privilege is not available to many researchers around the world. Taking into consideration the trend of increased demands and increased usage of simulators in the past years. Keeping in mind that the opportunity list is very seducing for both the academy and the industry to pursue simulator research for shaping a safer and a more efficient future for the maritime industry. Given these inputs, I think it is probable that the demand on simulator facilities will rise significantly in the next ten years and thus the usage of simulators in research will. The accessibility is a limiting factor in the growth of simulator research, however, technology advancements could provide solutions, such as virtual reality (VR) simulator technology.

The usage of simulators today, other than simulator-based education and training, is summarized as research towards education and towards developing technologies. It is interesting to harvest the fruits of the technology research part. Then, it is expected, quite soon, to see simulator usage embedded in industry processes such as ship design, port design, controllers design and the like. Such processes complement and support human-centred design frameworks that are essential methods for designing safety-critical systems and are recommended by the IMO. The next section is an analysis and discussion of the opportunities.

Opportunities

This section summarizes the opportunities of broadening the use of simulators. Simulators offer important 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 vessels will depend largely on simulator experiments. Starting with a brief about simulator advantages to lay the foundation for the opportunities.

Advantages

The advantages of simulators are massive, and here are several of them. First, simulators bring human-in-the-loop. The human user in the simulator is a central element of the performed operation. For the case of ship-bridge simulators, the human is the one observing, perceiving and interacting with the navigation equipment to achieve the desired maneuvers. Second, in the same manner, simulators bring the hardware in the loop as well. Real and up to date hardware is required to be installed in the

simulator for delivering the expected experience of realism. This requirement is valid for all interaction hardware, such as rudder and thruster controllers, seat, cabin / bridge furniture, radar screen and so on.

Third, simulators provide full control of the situation. A simulator is a safe lab to practice risky operations in harsh conditions. Fourth is feasibility. Running a demanding operation in a simulator is certainly dramatically more feasible than actually executing the operation itself. Instead of simulating the complete actual operation, concentrated chunks can be simulated to investigate or train the users for particular skill, thus saving time and resources. Fifth is Flexibility. The simulators offer flexibility in setting winds, waves and currents loads. In addition, it also offers flexibility in setting scenarios, the traffic, time, day and night, and so on. However, the flexibility is limited to designed flexibility. For instance, if the researcher requires enhancing the level of autonomy for the target ships, this cannot be done without further programming and software development.

Sixth, simulators run in real time, some of them have a capability in running faster than real time, and this property opens prediction and augmentation opportunities. Seventh simulator operations are reproducible. This is key property for research. The researcher is able to reproduce the conditions and perform the experiment over and over again.

And finally, simulators open new frontiers. They can simulate operations in very harsh and very rare weather conditions. They even can simulate cases not possible in real life. Such as planning iceberg management or optimization of seismic survey ship scan routes. A simulator center in Canada has developed a dynamic positioning (DP) controller for the arctic waters that accounts for wind, waves, currents and snow forces. A simulator center in Norway identified that seismic ship operators navigate differently and is investigating the optimal route for seismic survey navigation.

Proof of concept

Simulator runs come handy in the ability to validate or refute concepts regarding ship and port design. Not only valuable for proof of concept, but also for further developments and training. According to an interviewee, simulator runs can be used to train people, algorithms and procedures. Simulator experiments are crucial in the development of the following disciplines. First, research ideas can be validated in a simulator. For example, a researcher with own hypothesis: “separated traffic schemes will enhance safety in the sea” can structure simulator experiments to investigate the very existence of a relationship between the variables of interest. Second, algorithms can be trained in simulators and by simulators. Artificial intelligence algorithms require learning datasets. Datasets that teach the algorithm how things work in certain conditions. Simulators can provide valuable learning datasets for such algorithms. Then, the performance of the trained algorithm can be put under investigation in another simulator experiment.

Third is hardware. That is a two-folded opportunity. From the one hand, simulator experiments are used to verify and validate the performance of a piece of hardware, whether it delivers the actions as expected. From the other hand, an interviewee mentioned that learning curves of novice and experienced users could be investigated to evaluate the easiness and user-friendliness of the piece. Fourth, simulators are fit for purpose for evaluating new port designs. Pilots can run trials into and out of the port in a simulator with different ship sizes and test geometrical port features. Fifth, the use of simulators early on in the process of ship design. From maneuvering capabilities to bridge technologies, all can be investigated with operator in the loop in the simulator. Finally, simulators are the place to risk-free test interaction methods. Interface items such as controllers, visuals and bridge layout are subject to testing in a simulator for evaluating the impact of the changes on the performance of seafarer subjects.

Human factors

Simulators bring the opportunity to investigate group dynamics and interactions in a maritime operation setting. According to an interviewee, sociocultural variables could be considered and investigated in research such as gender differences, cultural differences, experience, and age differences. I think that “teamwork in critical operations” is a field that will benefit a lot from simulator capabilities. Simulator experiments also make observing the experts possible. An important data source for designers to learn how do experts really use and interact with the machine.

Development of methods

According to an interviewee, simulator involvement in the process of ship design for example is disrupting the industry practices and workflows. In line with HCD philosophy, the simulator becomes a regular meeting point among the designer, the owner, and the operator. I see that simulators can bring integrated operator’s experience and owner’s desires and constraints into the design process early on. This provides transparent exposure and understanding among project partners. Creating a paradigm shift in industry practices.

Another perspective for looking at this point is that simulator experiments reveal knowledge that was not

known before, this knowledge is used as a convincing tool to persuade the industry rethink their methods and practices.

Autonomous vessels

While investigating the safety and efficiency of different levels of autonomy, I think that simulators are the best havens for running numbers of scenarios and cases with all kinds of traffic mixtures involving autonomous vessels, remotely controlled ships, and conventionally-controlled commercial vessels including leisure boats and small fishing boats. The accumulated digital nautical miles provide experience and knowledge preparing the industry to take assured steps forwards. Simulators can also be the lab for testing guidance, navigation and control (GNC) algorithms.

Virtual ocean

As the numbers of simulators increase and their demand increases as well. I see that there is an opportunity of connecting simulator centers together and creating a digital model of the world's oceans, including coastlines and ports. Calling it the *Virtual connected ocean*, a shared ocean space for all kinds of ocean economy related research. Simulator centers can access the shared space and perform operations for research, training and technology development.

Anywise, when linking the current usages with the opportunities, then the imagination and the processing power are the limits of what a simulator can do. In other words, I believe that the scope of simulator usage is expected to grow significantly in the future. The next section is an analysis and discussion of the challenges.

Challenges

Simulators are technology driven. They advance together with technology advancements in computer processing power, graphics and visual systems and real-time hydrodynamic models. Despite of the state of the art, technologies do have their pitfalls occasionally. The challenges based on the experiences of the interviewed experts are summarized in this section. Part of the challenges is practical and is related to the setup, equipment, participants, and etc. The other part is philosophical, and is attached to the fact that a simulator is a simulator and reality is something else. Ironically, the philosophical challenges are closely related to the advantages of simulators.

Availability

The main challenge is availability. Simulators are physical rooms and there are some requirements need to be met before an experiment is ready to be held. According to interviewees, the challenge of the availability of the following was mentioned. First, the availability of simulators facilities. Researchers need to wait elongated periods sometimes in order to have a time slot for their simulator experiments. Second, the availability of experienced participants. It is not simple to book experienced seafarers for simulator experiments. They are not always available.

Third, the availability of technical support. An expert technician is required to help the researcher manage the data flows and logging. Additionally, to implement modifications on simulation configuration including scenario location, target ships, traffic, time, weather, equipment functionalities, and so on. Fourth and last, the availability of up-to-date interaction hardware is a challenge. Maintaining the feeling of the experience as realistic as possible, the full-scale up-to-date hardware is required to be installed, calibrated and connected in the simulator and be ready for use.

Data management

Big data volumes can be collected from a simulator experiment. Research infrastructure is required to enable researchers collect the data they seek otherwise it is very challenging to setup and achieve the desired data collection. Multiple possible data sources are there, and here are some examples. First, the ship data. This is mainly the data of the simulation software that holds quantitative information about the locations and motions of the ship(s) (i.e. location coordinates, course, heading, speeds, roll, pitch and other motions as they progress with time). Second, the navigation aids data, this include Radar images, ECDIS and AIS data. Third, the human-machine communication data, which is the record of all human control, inputs including thruster, rudder and other instructions.

Fourth, the human-human communication data. Whether it is communication among the bridge team, or communication between the bridge and others vessels, instructors or VTS. Fifth, physiological sensor data. This includes data from eye-trackers, heart-rate sensors, Electrocardiography (ECG), Electroencephalography (EEG), Electromyography (EMG), respiration sensors and temperature sensors. Note that wearing the physiological sensors on the body and keeping the wires connected is not only challenging, also heavy and motion restricting, thus the participant will be limited in motion and not feeling comfortable. Lastly, video data. Video recordings of the simulator session includes the bridges and instructor rooms brings valuable data for education and collaboration research fields.

Realistic physics and underlying assumptions

With the real-time constraint, the accuracy of the physics is not guaranteed in a simulation. The hydrodynamic models at the core of the simulator

software have underlying assumptions. In some conditions where such assumptions are physically invalid, the uncertainty in the computed ship response becomes high, thus, the simulator experience becomes less realistic. Unless, specialized hydrodynamic models where created and validated. Few examples of less realistic simulator experiences:

i. The last meter in a docking operation: as the ship is approaching into a dock, the behavior of the ship in the simulator gets less realistic. This is also true with approaching to any structure, such as ship-to-ship operations or sailing in a tunnel.
ii. Co-simulation: for example, the co-simulation of an offshore crane operation, the crane is mounted on the ship. The ship is moving in waves, the crane is lifting a load; the motion of the ship is affecting the motion of the lifted load and vice versa. The motion coupling is a non-trivial problem to solve. Therefore, the simulator experience deviates from the real world.
iii. Shallow water navigation effects are not appreciated in a simulator, because one of the underlying hydrodynamic assumptions is that the ship is sailing in deep water. However, there have been development of shallow water hydrodynamic models lately to cover this gap.

Software is software

Simulators, like other software, might have periodic problems, bugs and shutdown problems every now and then. According to interviewees, one expert technician per facility is required to maintain the simulators and perform both corrective and preventive maintenance measures. System updates increase the realistic functionality and feel, however it is typical, with every update, there is something lost that requires troubleshooting and fixing. The maintenance of a simulator facility is costly.

Philosophical challenges

A simulator experiment is not a real-life operation, yet, we desire them to be identical. The philosophical challenges are rooted from the differences of real-life operation conditions and simulator exercise conditions. For instance, the duration of the operation in real-life is long. It includes the trip to the location, the operation and the trip back, in which the operators live onboard. However, in simulator exercises, the participants would have a much shorter exercise, after which they can go home to relax and then have comfortable sleep. Real-life operators work longer shifts and they sleep with the ship motions, and would develop feelings of isolation. The duration, location, motions, seriousness and the overall feelings and thoughts of the operator would be different. This difference is related to the difficult question of validity and reliability of simulator experiments.

Discrepancies in results

In the literature review, one finding is the clear lack of published articles by authors with nautical science backgrounds. The nautical sciences are a new scientific tradition, very grounded in work and experience, while technologies are advancing fast and their involvement, as nautical scientists, in research and innovation is crucial for preparing the industry towards a better a future.

In the interviews there were no disagreements found, therefore, just the main agreements are highlighted. Regarding opportunities, 8 out of 9 mentioned statements that mean “simulators are tools for technology advancements such as the development of autonomous ships”. 5 out of 9 referred to simulators as good places for human factors research. 4 out 9 referred to simulators as enablers for developing processes, such as industry practices. Regarding challenges, 6 out of 9, expressed the urge of availability of expert help during simulator exercise. Help with managing the data and configuring the simulators is described as “indispensable”. 3 out of 9 agreed that achieving the realistic feel of the operator’s experience is quite challenging in a simulator.

CONCLUSIONS

Motives supporting the use of ship-bridge simulators in research, and thereafter, in the industry could be safety, efficiency and developing current technologies. A substantial share of the research work can be done in simulators, hence, simulators can be described as the safe havens and feasible laboratories for maritime research. They open new frontiers of research and development. Not only development of products and algorithms, but also the development of mindsets. Simulators gather people and gather disciplines together. Industry practices in design, for instance ship design, could change as a result of simulator research benefits. The IMO, since 2015, is recommending human-centred design approach in industry practices. This was a tangible result of simulator research. Simulators offer researchers multidisciplinary exposure, with engineer, seafarer, hardware and software in the loop. However, a gap in research is identified where the nautical domain education and expertise are needed and are encouraged to follow up.

The main opportunity for using ship-bridge simulators in research is the integration in the development processes of new technologies and designs. Whereas, the main challenge is the need of research infrastructure that includes technical support and appropriate tools for observation, collection and management of data.

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APPENDIX

Table 2: Presentation of the *Simulator Facility* category

Classification	Sub-classification	Publications' Names (a sample) and References
Simulator Facility	Evaluation of technology	"A Few Comments on Visual System of Ship Handling Simulator Based on Arriving Port" (Mitomo, Hikida, Murai, Hayashi, & Okazaki, 2008) "An experimental simulation study of advanced decision support system for ship navigation" (Nilsson, Gärling, & Lützhöft, 2009) "Accuracy of Potential Flow Methods to Solve Real-time Ship-Tug Interaction Effects within Ship Handling Simulators" (Jayarathne, Ranmuthugala, Chai, & Fei, 2015) (Arenius, Athanassiou, & Sträter, 2010; Bjørneseth, Dunlop, & Hornecker, 2012; Hontvedt, 2015; Jose Miguel Varela & Soares, 2017; Weber, Costa, Jakobsen, MacKinnon, & Lundh, 2018)
	Software for autonomous capability	"Deep Convolutional Neural Network-Based Autonomous Marine Vehicle Maneuver" (Xu, Yang, Zhang, & Zhang, 2018) "A user test of Automatic Navigational Intention Exchange Support System using an intelligent ship-handling simulator" (Miyake, Fukuto, Niwa, & Minami, 2013) "Developing a Maritime Safety Index using Fuzzy Logics" (Olindersson, Bruhn, Scheidweiler, & Andersson, 2017) (Ari, Aksakalli, Aydoğdu, & Kum, 2013; Benedict et al., 2014; Last et al., 2017; Wang, Yang, & Chen, 2011; S. H. Yang, Chen, Wang, & Yang, 2011)
	Software for fuel and emissions	"Effects of ship manoeuvring motion on NOX formation" (Trodden & Haroutunian, 2018) "Comparison of the Efficiency of Williamson and Anderson Turn Manoeuvre" (Formela, Gil, & Sniegocki, 2015)
	Software for human evaluation	"Quantitative projections of a quality measure: Performance of a complex task" (Christensen, Kleppe, Vold, & Frette, 2014) "A proposed Evidential Reasoning (ER) Methodology for Quantitative Assessment of Non-Technical Skills (NTS) Amongst Merchant Navy Deck Officers in a Ship's Bridge Simulator Environment" (Saeed, Bury, Bonsall, & Riahi, 2018) (Cohen, Brinkman, & Neerincx, 2015; Orlandi & Brooks, 2018)
	Software for specific operations	"A coupled kinematics model for icebreaker escort operations in ice-covered waters" (Zhang, Goerlandt, Kujala, & Qi, 2018) "Interactive 3D desktop ship simulator for testing and training offloading manoeuvres" (J. M. Varela & Guedes Soares, 2015) "Development of a Decision Support System in Ship-To-Ship Lightering" (Husjord, 2016) (De Souza, Tannuri, Oshiro, & Morishita, 2009; Șerban, 2015)

Table 3: Presentation of the *Experimental Practice* category

Classification	Sub-classification	Publications' Names (a sample) and References
Experimental Practice	Safety training	"A Comprehensive Experimental Practice for Ship Bridge Resource Management Training Based on Ship Handling Simulator" (Y. F. Yang & Feng, 2014) "Study on Dynamic Simulation System for Vessel's Collision Process and Its Application" (S. Yang & Chen, 2011) "Safety First: How simulating marine collisions can lead to a safer operating future" (Morter, 2015)
	Pedagogical approach	"The human factor and simulator training for offshore anchor handling operators" (Håvold, Nistad, Skiri, & Odegård, 2015) "On the Bridge to Learn: Analysing the Social Organization of Nautical Instruction in a Ship Simulator" (Hontvedt & Arnseth, 2013) "From briefing, through scenario, to debriefing: the maritime instructor's work during simulator-based training" (Sellberg, 2018)

		(Sellberg & Lundin, 2017, 2018)

Table 4: Presentation of the *Training and Evaluation* category

Classification	Sub-classification	Publications' Names (a sample) and References
Training and Evaluation	Evaluation of training technology	"An experimental simulation study of advanced decision support system for ship navigation" (Nilsson et al., 2009) "The human factor and simulator training for offshore anchor handling operators" (Håvold et al., 2015) "The AIS-Assisted Collision Avoidance" (Hsu, Witt, Hooper, & Mcdermott, 2009)
	Performance evaluation	"Systemic assessment of the effect of mental stress and strain on performance in a maritime ship-handling simulator" (Arenius et al., 2010) "Quantitative projections of a quality measure: Performance of a complex task" (Christensen et al., 2014) "Measuring mental workload and physiological reactions in marine pilots: Building bridges towards redlines of performance" (Orlandi & Brooks, 2018) (Kitamura et al., 2013; Murai & Hayashi, 2010; Murai et al., 2010)
	Technology on training	"Emergency Unberthing without Tug Assistance" (Kunieda, Yabuki, & Okazaki, 2015) "Energy-efficient operational training in a ship bridge simulator" (Jensen et al., 2018) "Fundamental Study of Evaluation at Berthing Training for Pilot Trainees Using a Ship Maneuvering Simulator" (Inoue, Okazaki, Murai, & Hayashi, 2013)

Table 5: Interview codes

Q1: Usage	**Q2: Opportunities**	**Q3: Challenges**
Education and training • Performing demanding tasks / operations • Individual and group training • Training novice and professionals • Leadership and joint situation awareness • Tools for enhancing safety and efficiency Research in education • Finding learning curves of student • Researching the learning in simulators • Instructor role in simulators Research in technology • Collecting physiological data • Testing new interaction designs • Data driven models for digital prototyping • Human in the loop research • Hardware in the loop research • Testing technology and algorithms • Mariner's response rates • Future projections • Offshore wind industry	Research and innovation facilitator • Innovation facilitator • Multidisciplinarity • Flexible scenarios • Connect simulator centers • Shallow water / bank effects • Docking • Complete control of situation • Proof of concept for new designs • Huge savings • Research teams / genders / cultures / groups • Training of algorithms / people / procedures • Observing the experts Developing industry workflows • Development of design methods • Convincing the industry New frontiers • Harsh environments • Autonomous vessels • More tests / scenarios / participants. Cases impossible in real life	Research infrastructure challenges • Availability of simulators • Availability of participants • Availability of technical support • Availability of maritime research partner • Data management • Availability of hardware Simulator being just a simulator • Limited setup flexibility • Duration of simulation • Location of simulation • Expensive to maintain • Bugs and shutdowns • Upgrade issues Technology readiness • Technology of sensors • Validity and reliability • Physics in co-simulation • Physics and visuals requirements • Mimic circumstances as good as possible