MAGPIE

SMART GREEN PORTS

D5.3 OFFSHORE CHARGING CONCEPTS DEMONSTRATION AND FEASIBILITY REPORT 3



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Khalid Tachi	WP leader	14/7/2026
Jose Sanchez	Peer reviewer	23/7/2026
Till Koesters	Peer reviewer	24/7/2026
Maarten Flikkema	Scientific coordinator	30-09-2026
Arne-Jan Polman	MAGPIE Coordinator	30-09-2026

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Abbreviations

ABS	American Bureau of Shipping
AIS	Automatic Identification System
BLT	Bluewater Loading Tower.
CALM	Catenary Anchor Leg Mooring
CTV	Crew Transfer Vessel
DNV-GL	Det Norske Veritas - Germanischer Lloyd
E&I	Electrical and Instrumentation
ELT	Electric Loading Tower
ESD	Emergency Shutdown
GMPHOM	Guide to Manufacturing and Purchasing Hoses for Offshore Moorings
HMI	Human Machine Interface
HV	High Voltage
HVSC	High Voltage Shore Connection
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
IEC	International Electrotechnical Commission
IP	Ingress Protection
LV	Low Voltage
LVSC	Low Voltage Shore Connection
MAGPIE	sMArt Green Ports as Integrated Efficient multimodal hubs
MARIN	Maritime Research Institute Netherlands
MBL	Minimum Breaking Load
MTU	Master Telemetry Unit
OCIMF	Oil Companies International Marine Forum
RTU	Remote Telemetry Unit
SOV	Service Operation Vessel
SPM	Single Point Mooring
STU	Shipboard Telemetry Unit
UPS	Uninterruptible Power Supply
WTG	Wind Turbine Generator

Executive Summary

MAGPIE is an EU-funded project under the Horizon 2020 research and innovation programme. It is an international collaboration working on demonstrating technical, operational, and procedural energy supply and digital solutions in a living lab environment to stimulate green, smart and integrated multimodal transport and ensure roll-out through the European Green Port of the Future Master Plan and dissemination and exploitation activities. The consortium, coordinated by the Port of Rotterdam, consists of 3 other ports (DeltaPort, Sines and HAROPA), 9 research institutes and universities, 32 private companies, and 4 other organisations. The project is divided in 10 main work packages which include energy supply chains, digital tools, 10 demonstrators for maritime, inland water, road, and rail transport, non-technological innovations and the development of a Masterplan for European Green ports.

Within MAGPIE, Demo 5 focuses on the offshore supply of electricity to vessels moored in waiting areas or operating near offshore wind farms. Its purpose is to assess the technical feasibility of safe and reliable offshore power transfer and to generate knowledge for further development, replication and scale-up. The overall objective of offshore charging is to enable vessels to switch off their engines and use renewable electricity while waiting or operating, thereby eliminating local emissions and reducing carbon emissions. In the longer term, offshore charging infrastructure could also be used to charge fully electric vessels. This can extend the benefits of shore power beyond the quay to port approaches, anchorages and other offshore waiting or working locations.

This report presents the concept development, technical feasibility assessment and demonstration of Bluewater's offshore charging solution within the MAGPIE project. It constitutes Deliverable D5.2.1 and covers the development and model-scale evaluation of the e-buoy concept and the subsequent demonstration of the Electric Loading Tower (ELT). Commercial viability, business-case development and the roadmap towards offshore recharging are addressed separately in Deliverable D5.2.2.

The e-buoy concept was developed from Bluewater's experience with turret CALM buoys and offshore mooring systems. It combines single-point mooring with a subsea power supply, high-voltage power transfer, a floating surface cable, cable reel, sliprings and a hawser arrangement. Service Operation Vessels were identified as the most practical initial application because of their operational profile and the expected availability of offshore power sources within wind farms.

The concept development confirmed that an offshore charging buoy can be defined in functional and technical terms. However, model-scale evaluation identified important limitations for the reduced-size buoy configuration in severe North Sea conditions. These

included significant buoy motions, snap loads in the mooring lines, high hawser loads and regular submergence in extreme waves. The floating hawser pick-up arrangement also raised concerns regarding entanglement and operational robustness. Consequently, the planned offshore demonstration with demo buoy C was not executed.

In line with the aim of the project and workpack, Bluewaters aimed to create and test a solution for offshore charging. Bluewater therefore assessed alternative offshore charging concepts. The ELT was selected as the most promising solution because it combines mooring and charging in a fixed structure, keeps the principal electrical equipment above the waterline and provides improved protection, accessibility and maintainability in harsh offshore conditions.

The ELT was demonstrated at MARIN using the Large Motion Simulator. The three-day campaign in March 2026 comprised 19 simulations covering approach, hook-up, residence, departure and emergency scenarios under varying environmental conditions. The simulations showed that the studied vessel had sufficient power to perform the assessed manoeuvres safely. Safe manoeuvring was demonstrated up to moderate North Sea conditions, while the vessel remained controllable, although with increasing difficulty, in more severe cases. The study also showed that the operational limits depend not only on vessel controllability, but also on the workability of the connection sequence and the exposure of personnel working on deck.

The work confirms that offshore vessel charging is technically and operationally credible, while demonstrating that the selected concept must be matched to the site conditions and intended application. For the assessed shallow-water North Sea application, the ELT provides a more suitable basis for further development than the reduced-size e-buoy configuration.

The results extend beyond the immediate wind-farm Service Operation Vessel application. They provide technical and operational input for offshore charging in waiting areas, anchorages and port approaches. Within MAGPIE, the findings support the further development, replication and scale-up of offshore charging solutions across the participating ports and contribute to the European Green Port of the Future Master Plan.

2. Introduction

2.1 Concept Development Background

Bluewater's intention is to develop a system to provide electric power to ships, near shore and offshore, based on Bluewater's knowledge on buoys and buoy operation.

The initial ideas for such an e-buoy were established end of 2020, after which the concept work started. A Bluewater patent application was filed in April 2021 and the patent was granted and published on 13 October 2022.

Bluewater agreed to participate in the MAGPIE project in February 2021, supporting the development of the e-buoy concept.

Bluewater needed to gain a more extensive understanding of electrical power to ships. This was established during the concept development work though meetings with wind farm operators, service vessel builders and service vessel operators.

It proved challenging to provide electric power to any type of ship. An electric power connection requires the ship to be prepared to receive the cable(s), the provided power needs to match the ships interface(s) and the control system needs to be aligned with the power supply system.

Ships, even when prepared for electric shore power, have a broad range of power needs and demand a diversity of voltages and frequencies. This variation in power and control requirements is reflected in the IEC standard 80005-1 ref [S3]. Therefore, Bluewater's efforts have focussed on providing electric power to purpose built full electric Service Operation Vessels (SOV), to enable a dedicated power and control interface.

Meetings with Service Vessel Operators builders and operators, such as IHC, Damen, Acta Marine, Chevalier and Bibby provided insight in the requirements for an electric power supply in wind farms and SOV operations. Similarly, wind farm operators such as Vattenfall, Shanghai Electric and Shell contributed to an understanding of the marked and needs.

A power supply for a Crew Transfer Vessel (CTV) has been briefly discussed with Damen. This was put on hold because such small vessels require a Low Voltage DC power connection.

Heerema MC provided insight and lessons learned in their project for shore power to the Thialf crane vessel, especially regarding the protection of the power cables, the HV power connectors and the fibre optic connection.

The e-buoy concept was developed, based on Bluewater's knowledge of the Turret CALM buoy. The development process and steps undertaken are documented in this report.

2.2 MAGPIE Project

2.2.1 Project Brief

Bluewater agreed to participate in the MAGPIE project in February 2021, supporting the development of the e-buoy concept for the Port of Rotterdam. This EU funded project consists of a number of work packages related to concept development, testing and demonstration of innovations, with the aim to contribute to the greening of port operations.

The e-buoy is part of the MAGPIE Work Pack 5.2, titled 'Re-fuelling buoy'. This work pack includes the following scope for the e-buoy development (not exhaustive):

- Buoy A : Concept design of a power supply e-buoy for large ships;
- Buoy B : Concept design of a power supply e-buoy for SOV's;
- Buoy C : Design, fabrication and demonstration of a demo e-buoy.

The objective of the e-buoy task to determine the technical and commercial viability of an offshore electrical charging station, using a buoy for temporary mooring as well as for transfer of electrical power.

This is to be demonstrated by numerical design, evaluation and demonstration tests at model scale and at large scale. While the CALM buoy and its mooring system is considered proven technology, the transfer of electrical power to a ship moored to a buoy is new technology.

For MAGPIE deliverable D5.3, the present report is proposed to be positioned as the technical feasibility and concept development report for the e-buoy concept and the associated model-scale evaluation. The technical assessment presented here should be read together with the dedicated model test / M&S reporting. Commercial viability, business case development and the roadmap to offshore recharging are addressed separately in deliverable D5.4.

In line with the wider MAGPIE scope, the findings of this study are not limited to the immediate wind-farm service vessel charging use case. They also provide input to future offshore charging applications, including waiting areas and anchorages, where the long-term potential of offshore charging concepts may justify further development even where immediate implementation is not yet feasible.

2.2.2 Concept Development Scope

To start the development of an offshore power to ships system, a business case examination is to be performed, providing an understanding of the market and the requirements for such a system. Such a business case examination also provides a basis to determine the economic viability of the system.

The results of the market survey shall consider system requirements, such as type and size of moored vessels, power characteristics, possibly locations with indication of water depth and environmental conditions, system availability and other requirements that an e-buoy system should be based on. Using these requirements, Bluewater shall provide concept designs for Buoy A and Buoy B, including:

- The mooring buoy with its mooring system;
- The electrical power and control system;
- An assessment to identify the potential (technical) risks and mitigations;
- An operability review including marine operations descriptions;
- A roadmap for further development;
- Indication of Capex and Opex cost.

Based on the experience gained in the project, Bluewater shall provide a roadmap for the further development of the offshore power to ship system, addressing remaining challenges, including those related to statutory regulation, liabilities and missing rules and standards.

2.2.3 Model Test Scope

The model scale tests are performed in a basin using a realistic environment at a scale of about 1:20 to 1:30, allowing an accurate observation of hydrodynamic behaviour and prove of viability of technical components.

MARIN shall perform the demonstration tests in their Shallow Water Basin. The test includes an advanced 'Software in the Loop' (SIL) modelling approach to impose the motions of the moored vessel onto the power cable and the mooring hawser.

2.2.4 Demonstration Test Scope

Bluewater developed the concept for the demonstration e-buoy (C) as part of the original MAGPIE scope. The original purpose of the planned demonstration was to validate the mechanical robustness and operability of the system, with special focus on the marine operations. A MultiCat vessel (or equivalent) is foreseen, modified to enable mooring to the hawser and to include a cable hang-off connection arrangement at the bow.

The offshore demonstration with demo buoy C was not executed. The change in demonstration approach, including the reasoning for shifting to a separate simulation / ELT-based route, is addressed from chapter 10 in this report. The objective of the demonstration is a proof of concept for an offshore charging system , allowing a single point mooring and a power cable connection to ships, demonstrated by:

- Connection operation of both a hawser and the electrical power cable;
- Disconnect operation;
- Emergency disconnect operation.

The marine operations for the mooring and cable handling will be monitored and evaluated to provide valuable lessons learned for this type of operation.

2.2.5 Deliverables

The MAGPIE reporting package for this scope comprises the following documents:

- D5.3 – this report: concept development of offshore charging, technical feasibility assessment and demonstration
    - Annex 2 of this report- Dedicated model test / M&S reporting, including the MARIN-related evaluation documents;
    - Annex 3 of this report - A separate demonstration report, covering the revised demonstration route and lessons learned;
- Deliverable D5.4 – business case report and roadmap to offshore recharging.

3. Electric Power to Ships

3.1 Power Requirements

Countries worldwide are set on a strategy to reduce greenhouse gas emissions and pollution, with legislation being put in place to act. The shipping industry is a substantial contributor of these emissions and efforts to improve include alternative fuels and zero-emission at berth, such as shore power systems.



Figure 1: Stena shore power supply system in Hoek van Holland (Rotterdam)

The number of shore power systems in ports worldwide is increasing. Generally, the systems for larger ships comply with the IEC standards for Shore power.

The standard for HV shore power systems is IEC 80005-1/2, ref [S3] and ref [S4]. The standard for HV shore power connectors is IEC 62613-1/2, ref [S1] and ref [S2], up to a maximum voltage of 12 kV (AC) and a maximum current of 500 A.

The IEC standards show a variety of requirements for the power connection for the different types of ships, including the number of power cables and the associated control system. Furthermore, the power demand for ships varies with size and type. Considering this diversity, it is not deemed feasible at present to design an offshore system able to provide electrical power to such a broad variety of ships.

It is highly desirable, for both shore and offshore power systems, to have a more scalable system with matching requirements for all ships; including the voltage (e.g. 6.6 kV and 11 kV), the frequency (e.g. 50 Hz), the control system and the HV connectors. The power demand for each vessel could be matched by means of setting the voltage and connecting the required number of power cables (e.g. 1 up to 4). Whether this is practical needs to be assessed.

An approximation for the (off) shore power demand for various sizes and types of ships is shown in Table 1. A shore power connection for larger ships is generally 6.6 kV or 11 kV.

Vessel type	Apparent Power		Voltage (AC)		Power Cables	
	Min [MVA]	Max [MVA]	Min [kV]	Max [kV]	Min [Qty]	Max [Qty]
Assumed power demand for an offshore supply system						
CTV (offshore)	0.2	0.5	0.7 … 1 DC		1	
SOV (offshore)	4	9	6.6	11	1	
RoRo	1	8	6.6	11	2	
Ferry	3	15	1 DC	11		
Mid size <140 m	1	3	6.6	11	1	
Large size >140 m	3	6	6.6	11	1	2
Cruise <200 m	2	7	6.6	11	1	2
Container ship	5	7.5	6.6		3	
Cruise >200 m	7	10	6.6	11	1	2
Tanker	5	10	6.6		4	
Cruise >300 m	10	15	6.6	11	2	3
Cruise (general)	16	20	6.6	11	2	4

Table 1 – Diversity in Power Demands for Ships (examples)

Power demands are diverse and very much depending on the type of ship and its application. For example, a full electric Ferry requires using quick charging while she is (off) loading, needs high power due to the short charging time. A fuel powered vessel does not need charging but requires power for her systems while she is moored, which can be small or substantial, e.g. in case of Cruise Vessels.

The estimates for the CTV's (Crew Transfer Vessels) and SOV's (Service Operation Vessels) has been obtained from various (internet) sources, vessel data and discussions with vessel builders. Small vessels such as CTV's seem to require low DC voltage, which can be considered in future developments of offshore power systems.

In principle, the system for offshore electrical power to ships is similar to shore power systems. At present, for an offshore electrical power supply it is practical to design for a dedicated vessel type, such as an SOV. The type of SOV operations and the proximity of a power source make an SOV the ideal first application, with SOV manufacturers already working on full electric designs. The SOV design would incorporate the ability to connect to an offshore power system, including the power cable interface and the control interface. A purpose-built system for an offshore application should observe the IEC standards for shore power, especially since such vessels are configured to receive shore power. The system should be fully standardised to allow electric SOV's to operate and charge in any wind farm, especially considering that these vessels are often chartered by the wind farm operator.

The voltage considered for an offshore power supply for SOV's is 6.6 kV (AC) or 11 kV (AC). This enables sufficient power transfer and allows bridging a distance to the power supply, which is likely the wind farm substation or a wind turbine. DC power supplies have not yet been considered.

The use of a single power cable connecting to the SOV is considered practical for offshore connect and disconnect operations. A standard IEC HV connector enables to provide

power up to 11 kV and 500 A. This equals 9.5 MVA or approximately 8.5 … 9.0 MW depending on the power factor, which should be sufficient to charge the batteries of a full electric SOV within the available operational time slots.

The use of higher voltages, e.g. 33 kV, or alternatively higher currents could be considered for a dedicated offshore power supply above 9.5 MVA using a single cable. Alternatively, a number of power cables can be used in a bundle, which is desirable for marine operations to prevent entanglement.

4. Wind Park Service Vessels

4.1 Service Operation Vessel (SOV)

Purpose-built Service Offshore Vessels (SOV's) are 70 m to 100 m long vessels. These vessels operate in the remote wind farms, where a land-based service organization is not practical. During service operations, the SOV efficiently sails around the wind farm, transferring technicians to the wind turbines and collecting them after the service work is completed, while providing them with a temporary home for several days/weeks. About 40 to 60 technicians live on-board a SOV and the transfer to and from the wind turbines is performed with motion compensated walk-to-work gangways. The work is performed in 12-hours shifts, preferably during daytime.

Such planned service works on wind turbines is generally executed from spring to autumn, with the SOV's mostly staying in port during winter months, although there could be a need to work all year round.

The gangways can be safely operated in waves of 2.5 m Hs, in some cases up to 4 m Hs. The SOV itself is designed as a seagoing vessel, capable to withstand much harsher conditions.



Figure 2: Service Operation Vessel (Royal IHC)

4.1.1 SOV Operations Weather Window

From interviews with SOV operators, it was learned that in case of rough weather the SOV tends to seek shelter in areas with lower wave height such as shallow water or the leeward side of the wind farm. This is mainly done to avoid motion sickness amongst the turbine technicians and other crewmembers. The SOV typically remains in the wind park up to wave heights varying between 2.5 m Hs to 3.5 m Hs, depending on the SOV size, weather forecast, the decisions made by the captain (and client) and the comfort of the technicians and other crew members.

Similarly, the limitations to connect to a system for charging is driven by wave height and weather forecast. It is expected that such connect and charging operations shall be performed in wave heights of 2.5 m Hs up to 3.0 m Hs.

Considering the metocean data for 'Doggerbank A' ref [R1], a North Sea wind farm in a water depth of 19 to 35 m, it can be estimated that during the period mid-April to mid-September, the wave height is generally below 2.5 … 3 m Hs. During this period, a 12-hour weather window with waves less than 3 m Hs is often available, taking into account a waiting time of a few hours. The prediction for April and September is a wave height less than 3 m Hs for 93% of the time. June and July are the calmest, with waves less than 3 m Hs for 98% of the time.

During March and October, the availability of such 12-hour weather window is reduced, and a waiting time up to 12 hours can be expected. The prediction for March and October for a wave height less than 3 m Hs is 86% of the time.

During November to February, an SOV is typically not expected to operate permanently in a wind farm. One can imagine day trips are undertaken to cope with unexpected events without the need for charging or using the back-up combustion engines. In this period, the availability of a 12-hour weather window with waves less than 3 m Hs is unfavourable and a waiting time up to several days can be expected.

4.1.2 SOV daughter craft

SOV's can be equipped with daughter craft, which are usually small mono hull vessels similar to small rescue crafts. SOV daughter craft are for example 10-12 m in length and can transfer personnel to wind turbines in benign wave conditions such as 1.0 … 1.2 m Hs.

Considering the metocean data for 'Doggerbank A' ref [R1], it can be tentatively concluded that operation windows for such daughter craft are mostly available in June until August, with a prediction for the wave height being less than 1 m Hs for roughly 50% of the time. During this period, the availability of 12-hours weather windows to operate daughter craft seems to be limited to a couple of days a week.

Full electric SOV daughter craft can be easily charged during the night, when the craft is brought aboard the SOV. The DC charging power would be supplied from the SOV's systems.

4.2 Crew Transfer Vessels

Crew Transfer Vessels (CTV), also called Fast Crew Supplier (FCS) are fast travelling vessels used to service wind parks. CTVs are typically light catamaran type vessels with 15-to-28-meter length. The larger CTVs are built to cope with the demand for an increased operational weather window, allowing them to operate in wave height e.g. up to 2 m Hs. Fast crew transfer vessels operate from a port to service nearby wind farms and typically return to their land base each day. CTVs cannot carry large battery packs, which limits their range of operation. Being able to charge in the wind farm would make full electric CTV's feasible for more remote locations.

A power supply for a full electric Crew Transfer Vessel (CTV) has been briefly discussed with Damen, requiring 700 V (DC) and 200 kW. Because the CTV is a light and small vessel, it is not able to accommodate a transformer and preferably requires a direct Low Voltage DC power connection.

The distance between an offshore charging system and the power source, typically the wind farm substation or a wind turbine is assumed minimum 500m to 1000m for reasons of safety. A low voltage DC supply system from the power source was considered impractical due to the required size of the subsea power cable; higher voltages are required to bridge the distance. The offshore charging system would likely need to be equipped with a transformer, rectifier and control interface system to enable such a LV DC power supply. This is feasible but was considered low priority in this phase.

Alternatively, when an SOV and CTV are working in pairs, a CTV could receive a Low Voltage (e.g. 700 V) DC charging connection from an SOV.



Figure 3: Damen built fast crew vessel for Rederij Groen

5. E-buoy Concept

5.1 Basic Concept Philosophies

For an offshore electrical power supply, it is practical to initially design for a dedicated vessel type, such as an SOV operating in a wind farm. The type of SOV operations and the proximity of a power source make an SOV the ideal application, with SOV manufacturers already working on full electric designs.

Many offshore wind farms are in a water depth range of 20 to 40 m, with developments of future wind farms in deeper water. This water depth range is the main technical criterion for the selection of a buoy system as the leading concept for an offshore electrical power to ship system. A buoy system can be easily adapted and applied in a range of water depths. Bottom founded (tower) systems can be considered for more shallow water.

Based on Bluewater's experience with offloading buoys and associated floating hoses, a floating cable system between the buoy and the vessel is selected. The surface cable with the vessel connector is reeled into the buoy, to prevent fatigue damage to the surface cable, to allow easy access to the connector if needed and prevent the cable to be damaged or entangled with the buoy or the mooring system.

The system should preferably allow for hawser mooring and free weathervaning, allowing the vessel to minimise its power consumption during charging. Charging while keeping station on Dynamic Positioning (DP) was initially not advised by SOV manufacturers, due to the envisaged power consumption of the propulsion system. However, the possible benefits of such a DP charging operation should be considered in future developments since this is beneficial for the marine operations.

The hawser mooring and cable connection are preferably separate operations, first ensuring berthing followed by the handling of the power cable.

The concept for the mooring hawser is permanently floating, identical to the system used on a standard offloading buoy system. It is noted that such floating hawser in harsh conditions is likely to experience entanglement issues. Alternative solutions can include a hawser reel or hawser parking by means of a clump weight.

The use of existing components, either from the offshore industry or another industry is highly preferred. The development and qualification of new components or equipment have proven to be a lengthy and costly process, without the guarantee of success.

Unlike the marine operations of a standard buoy system, the operation to connect to an offshore charging system is to be performed by the crew of the vessel, without the assistance of tugs, small boats or daughter craft. An operational requirement to routinely access the buoy, other than regular maintenance or inspection, is considered not acceptable. The operation should obviously be safe, but also easy and protected by means of safeguards and automation.

The master control and monitoring of the overall system is preferably located on the vessel. For the hook-up operation, the initial communication between the vessel and the e-buoy is by means of telemetry. After berthing and cable connection, the communication between the vessel and the e-buoy shall be hard wired. The communication between the e-buoy and the power supply is through fibre optic or telemetry.

A weathervaning e-buoy system requires a slipring to transfer the power from the geostationary subsea cable to the rotating buoy body. Furthermore, the surface cable is to be retracted, requiring a reel system, which also requires a slipring. These high voltage slipring assemblies are a significant investment. It was therefore decided to use a single slipring for both weathervaning and reeling, by means of combining the axes of rotation of the buoy and the reel. The reel therefore has a vertical axis of rotation.

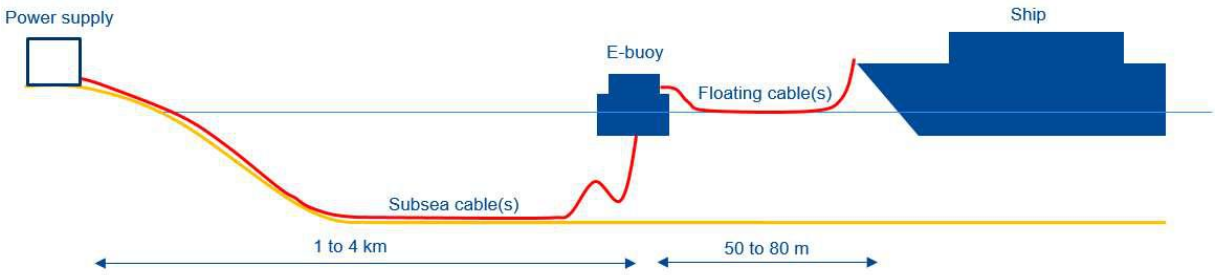


Figure 4: Concept sketch of the e-buoy system

5.2 Bluewater Patent

The Bluewater patent for the e-buoy system was granted and published on 13 October 2022, under the International Publication Number WO 2022/216151 A1, titled 'Assembly for transferring a medium to a vessel and vessel for use therewith'.

5.3 Concept Evolution

5.3.1 Buoy Type

Typical CALM buoy systems are so called Turntable or Turret types. Various configurations of both types have been assessed, considering the location of the electrical and control equipment.

The Turret buoy was selected since it is equipped with a deckhouse, providing protection for the high voltage equipment and its improved stability, especially considering the harsh North Sea environment with high and especially steep waves in extreme conditions.

Initially a standard 10 m buoy size was selected, the smallest size CALM buoy built by Bluewater. Considering the size and displacement of an SOV compared to a crude tanker, it was decided to reduce the buoy size. An 8 m diameter buoy was used in the Model testing at Marin. The results of the model test were not favourable, showing snap loads in the mooring lines, high hawser loads, significant buoy motions and regular submerging of the buoy in extreme waves. This is further addressed in the reporting of the mooring system and model testing.

5.3.2 Floating Cable

The development of a special floating cable has been avoided, relying on available components. To allow reeling, the floating hose should preferably not be equipped with flanges. Long length hoses op to 300 m are available in a soft wall (fabric reinforced) and

BETTER SHIPS, BLUE OCEANS

E-BUOY MODEL TESTS

Hydrodynamic Model Tests

Text Report - Final

Report No.	:	33350-2-BT
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E-BUOY MODEL TESTS

Hydrodynamic Model Tests

Text Report - Final

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DOCUMENTATION SHEET: Shallow Water Basin

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REVIEW OF DELIVERABLES – PROJECT

Deliverable type		Content
Text report	2022.06 MAGPIE Demo5_MARIN model tests	Model Test Plan
Text report	MARIN report No. 33350-2-BT	Model Test Report
Internet: MARIN website, LinkedIn	https://www.marin.nl/en/news/horizon-2020-magpie-e-buoy-for-charging-at-sea	Model Test Post
Presentation at Public event	Offshore Charging buoy presentation at Blueweek	Presentation
Article	MARIN Report 134	Article Offshore Charging

REVIEW OF DELIVERABLES – PRESENT TASK

Report type		Content
Text report	MARIN report No. 33350-2-BT	Model Test Report (present report)
MARIN FTP and Hard Drive		Data analysis Video recordings (Hard Drive only)

EXECUTIVE SUMMARY

The EU H2020 MAGPIE project focusses on greenification of ports. The project is coordinated by Port of Rotterdam (POR). Task 5.2/ Demo 5 consists of the design and evaluation of an e-loading buoy. As part of WP5.2, DEMO 5, TRL5 hydrodynamic model tests are performed by the Maritime Research Institute Netherlands (MARIN). These hydrodynamic model tests allow to verify the Demo Buoy design, denoted Buoy C, prior to the TRL6 offshore tests in the next steps of the project. Furthermore the hydrodynamic model tests provide input for tuning and verification of numerical models to further evaluate Demo Buoy and Prototype Buoy designs.

Models and setups

Two buoy designs are evaluated in the model tests: the Demo Buoy C and Prototype Buoy B. The buoys are represented at different model scale (1:11 for Buoy C and 1:25.77 for Buoy B) to maximize the model sizes, while being able to generate the design wave conditions (1yr summer storm for Buoy C; 100yr storm for Buoy B).

The tests were performed in MARINs Shallow Water Basin. The following tests setups have been installed and applied in the basin during the test programme:

- Wave calibrations without the models in the basin.
- Setup B1: Buoy B only (including mooring and seabed cable), without floating hose and SOV
- Setup B2: Buoy B (including mooring and seabed cable); with floating hose, hawser and SOV
- Setup B3: Buoy B (including mooring and seabed cable); with floating hose and SIL* SOV
- Setup C1: Buoy C only (including mooring and seabed cable), without floating hose and SOV
- Setup C2: Buoy C (including mooring and seabed cable); with floating hose, hawser and SOV
- Setup C3: Buoy C (including mooring and seabed cable); with floating hose and SIL* SOV and MultiCat

* *Software-In-the-Loop SOV and MultiCat: numerical representations of the bunkering vessels on DP in current, waves and wind. The numerical bunkering vessels are added to the physical test setup through Software-In-the-Loop (SIL) models.*

Tests

The survivability of the Buoys was evaluated in Buoy only tests (Setups B1 and C1). In these tests buoys are free to weathervane. In general the buoys weathervane such that the appurtenances are at the leeward side of the buoys. In some cases buoys show large yawing motions. Some rotations occur rapidly due to extreme wave events and asymmetry first order yaw loading. Other rotations are slow due to asymmetric wave drift loading.

During extreme event the following typical behaviour occurs:

- A steep breaking wave overtops the buoy completely and gives it a rapid horizontal setback. This results in peak loads of the wave ward mooring line. For Buoy C water enters the deckhouse through the hose opening.
- When the wave has passed the buoy restores and overshoots in wave ward direction. This results in slack of wave ward mooring line and a peak load of leeward mooring line. The skirt and underside of the buoy come out the water, slamming occurs.

Water overtopping the buoys, high mooring line loads in the wave ward lines, slack mooring lines and slamming on the skirt occur during extreme wave events. It is recommended to take the risk and effect of water overtopping the buoy and of slamming loads on the skirt into account in the design of the buoys.

For the tested sea states the response transfer functions of Buoy C without the hawser attached (Setup C1) are mostly linear. With the hawser attached (Setup C2 and C3) the modes of motion in-line with the waves and SOV (surge and pitch) are affected by the hawser loads. The motions of the buoy, especially

pitch, follow the response of the SOV and hawser, mainly increasing the low frequent motions of the buoy.
The response of the hawser loads increases when Backward Pull is applied by the bunkering vessel (0t, 1t, 2t in Setup C2).
When 1t Backward Pull is applied by the SIL model (Setup C3), the low frequent hawser loads are less than when the 1t Backward Pull is applied by a wire at the stern of the SOV. This indicates the low frequent phenomena are underestimated by the SIL approach; the wave frequent hawser loads are overestimated.
With a DP system applied through the SIL model the hawser loads and low frequent motions of the buoy reduce significantly. It is therefore recommend to use DP control of charging vessel iso Backward Pull.
The motions of the buoy and loads in the hawser are similar for cases where the MultiCat is connected (by means of the SIL model) as where the 44m SOV is connected.

The motion RAOs of the SOV are not influenced by the hawser. They are influenced by transverse standing waves in the basin, due to reflections from the vessel and buoy, once compared to undisturbed RAOs from diffraction analysis.

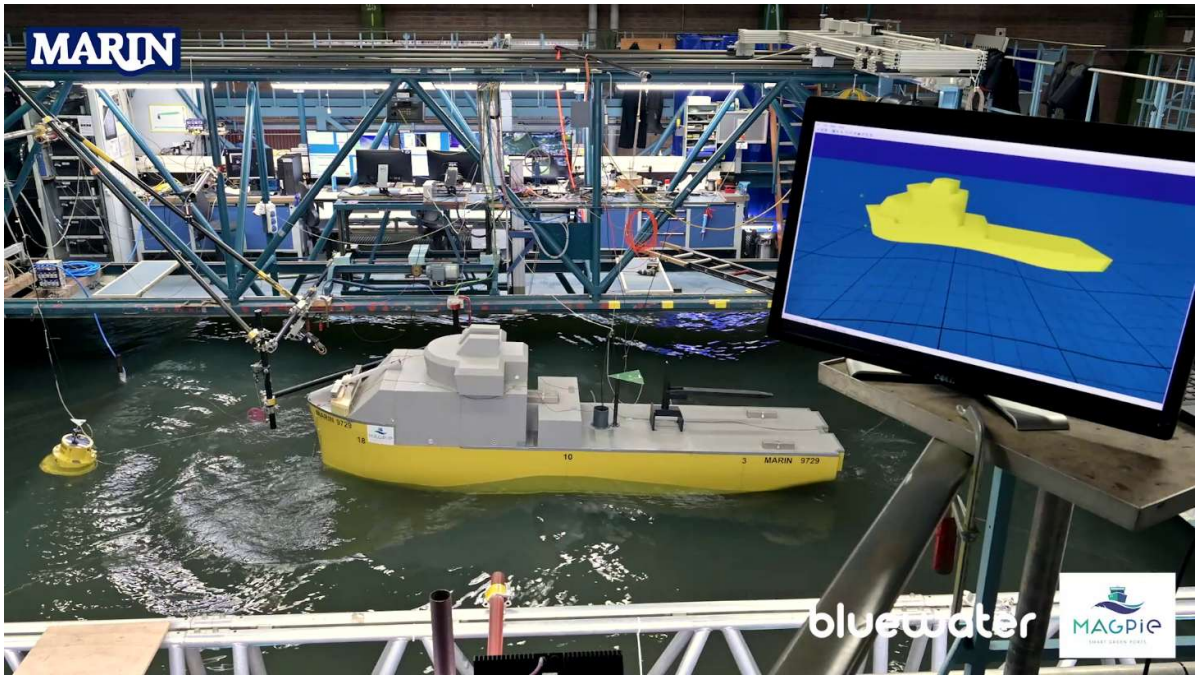


Figure 1-1: Video still of model test Buoy C, SOV and software-in-the-loop modelling

1 INTRODUCTION

1.1 Background

The EU H2020 MAGPIE project focusses on greenification of ports. The project is coordinated by Port of Rotterdam (POR).

Task 5.2/ Demo 5 consists of the design and evaluation of an e-loading buoy. The task description given in the EU proposal is copied in Annex 1. The task is coordinated by Bluewater (BES). Partners are MARIN, POR and Van Oord (VO). Part of Task 5.2 are numerical simulations and scale model tests performed MARIN.

1.2 Objectives

The objectives of the model tests are:

TObj1 Evaluate the hydrodynamic behaviour of Buoy C (DEMO) and Buoy B (PROTO) in operational and survival conditions.

TObj2 Collect model test results for verification of the hydrodynamic behaviour of the Buoy C. (DEMO) without and with bunkering vessel. The model tests results will be used in correlation analysis with numerical simulations and full scale measurements.

TObj3 Collect model test results for verification of the hydrodynamic behaviour of the Buoy B. (PROTO) without bunkering vessel. The model tests results will be used in correlation analysis with numerical simulations.

TObj4 Evaluate the integrity of subcomponents:
- seabed power cable (Cable JIP II crossover interface)
- hawser + e-loading cable i.e. buoy-ship connection
- mooring system

TObj5 Establish modelling and evaluation methods (physical and numerical) of flexible floating hoses.

1.3 Approach

The following approach is followed to fulfil the objectives:

- The model tests are be performed in MARINs Shallow Water Basin, see Section 3.1.
- Buoy C DEMO and Buoy B PROTO are represented on different model scales to maximize the model sizes, while being able to generate design wave conditions. The model scales are described in Chapter 3.
- A hybrid model test approach is followed. The hybrid test approach consists of physical representations of the buoys in waves only and numerical representations of the bunkering vessels on DP in current, waves and wind. The numerical bunkering vessels are added to the physical model test setup through Software-In-the-Loop (SIL) models. The test setups are described in Section 3.2.
- MARINs stock SOV model will be used in the tests to set up and verify the SIL modelling approach. The numerical SIL model will represent the SOV as well as the MultiCat.

1.4 Content of the report

In this report the following topics are addressed:

- Description of the sign conventions
- Description of the facility, setup and models used for the test campaign
- Description of the environmental conditions
- Description of the measurements and data acquisition
- Description of the test matrix
- Description of the experimental procedures
- Discussion of the results
- Conclusions and recommendations

2 SIGN CONVENTIONS AND DEFINITIONS

2.1 General conventions

The following general conventions are used in this report:

- All results are presented as full scale values unless explicitly stated otherwise.
- The metric system of units (SI) is used.
- A right-handed co-ordinate system is used with the positive z-direction upwards.
- All reported values are absolute values with respect to the design position.

2.2 Scale factor

Model tests were performed for the following buoys and associated scales:

- Buoy C (DEMO): 1:11 scale version for tests in Operational (1yr, summer) conditions.
- Buoy B (PROTO): 1:25.77 scale version for tests in Survival (100yr, 10yr, 1yr) conditions.

All results of the model tests are presented as prototype values in the tables and figures in this report unless denoted otherwise. The model tests results are converted from the model scale values applying Froude's law of similitude. For scale λ of 1:11 / 25.77, this means that the conversion factors of Table 1 are applied.

The ratio ρ_1/ρ_2 = 1026 kg/m^3 / 1000 kg/m^3 between the specific weight of salt water and the fresh water in the basin indicates that all test results apply to seawater.

2.3 Sign convention

General descriptions of the Basin Fixed sign convention and Ship Fixed sign convention are given in Appendix F06 and I05. The present section describes the application in the present project.
Definitions are given in Section 2.4.

2.3.1 Basin-Fixed coordinate system

During the tests the Buoys were positioned at 25% of Basin Length away from the wave maker, on basin centreline. This is denoted as the Design Position. The Basin Fixed coordinate system is defined at this location with positive x-axis towards the waves and right handed coordinate system. See Figure 3 and Figure 9.

The buoys are positioned with their Local Coordinates Systems at (X,Y = 0,0 m) and with 0° heading in the Basin-Fixed coordinate system.
The SOV is positioned with its Local Coordinate System X = - 82.01 m in the BFCS for Buoy B and X = - 49.34 m for Buoy C.

2.3.2 Ship-Fixed / Local coordinate system

The Local Coordinate System (LCS) of the buoys/ vessel has its origin at buoy/ vessel midship (X,Y = 0,0 m) and keel (Z = 0.0 m). Right handed coordinate system.

The direction of measured forces, accelerations and motions are referred to the LCS.

The motions are positive in the following directions:

positive surge	(x)	:	towards the front/ bow
positive sway	(y)	:	towards port side

positive heave	(z)	:	upwards
positive roll	(ϕ)	:	starboard side down
positive pitch	(θ)	:	bow down
positive yaw	(ψ)	:	bow towards port side

The forces and moments are positive in the following directions:

positive longitudinal force	(F_x)	:	towards the front/ bow
positive lateral force	(F_y)	:	towards port side
positive vertical force	(F_z)	:	upwards
positive roll moment	(M_x)	:	starboard side down
positive pitch moment	(M_y)	:	bow down
positive yaw moment	(M_z)	:	bow towards port side

The following relation applies between the BF environmental direction, SF environmental direction and the orientation of the buoys:

$$\mu_{SF} = \mu_{BF} - \Psi_{BF}$$

in which:

μ_{SF}	:	Ship Fixed (SF) environmental direction
μ_{BF}	:	Basin Fixed (BF) environmental direction
Ψ_{BF}	:	Basin Fixed (BF) vessel heading

Note the initial SF wave direction was always 0°, while the actual SF wave direction varies with the heading of the buoys during the tests. During all tests the buoys were free to weathervane due to the rotatable turret between the mooring and the buoys.

2.4 Definitions

In the volumes of this report the following terms are used:

Basin Fixed coordinate system (BFCS)	Coordinate system with origin at the Design Position in the basin and waterline. Right-handed coordinate system with positive x-axis towards the waves, Figure 3 and Figure 9.
Local Coordinate System Ship-Fixed coordinate system (SFCS)	Buoy/ vessel coordinate system with origin at Buoy/ vessel midship (X,Y=0,0) and keel. Right handed coordinate system.
Heading / orientation (Ψ_{BF})	Orientation of the local coordinate system in the BFCS. During the tests the LCSs was 0° i.e. aligned with the BFCS.
Basin Fixed (BF) environment (μ_{BF}):	Environmental direction with respect to the BFCS. Environments were applied from 180° in the Basin Fixed direction.
Ship Fixed (SF) environment (μ_{SF}):	Environmental direction relative to the floater. Definition according to Ref [2]. During the tests only 180° SF environmental conditions were applied.
Design position:	25% of Basin Length away from the wave maker, on basin centreline. The vertical position is at the waterline. This position corresponds to the centre of the mooring system and the centre of the Buoys with mooring only (no offset). All reported offsets are given with respect to this position.

	At this position all measurement signals are zeroed. For a description of the zero procedure see Section 6.2.3. At this position the absolute values of all measurement signals are registered after installation of the Buoys. Thereafter the measured signals are zero-ed. The registered absolute values (so-called zero values) are added to the measured values in post-processing.
Equilibrium / Zero position:	Location of the Buoys/ vessel at rest in calm water. Natural, free floating position of the Buoys with mooring lines and seabed cable attached.
Low-Frequency	Low-frequency is defined as a response with frequencies from 0.00 till 0.30rad/s.
Wave-Frequency	Wave-frequency is defined as a response with frequencies varying from 0.25 to 2.00 rad/s.

3 FACILITIES/ SOFTWARE, EXPERIMENTAL SETUP AND MODELS

3.1 Facility

The tests are performed in MARINs Shallow Water Basin. This basin is equipped with a wave maker at one side of the basin, current and wind can not be generated. The basin is especially suitable for testing in near shore (shallow water) conditions. A detailed description of the capabilities of the Shallow Water Basin is given in Appendix F06.

The water depth in the basin was set at 1.0 m on model scale. Representing 25.77 m for the tests with Buoy B and 11.0 m for tests with Buoy C.

3.2 Test setups

The following tests setups have been installed and applied in the basin during the test programme:

- Wave calibrations without the models in the basin.
- Setup B1: Buoy B only (including mooring and seabed cable), without floating hose and SOV.
- Setup B2: Buoy B (including mooring and seabed cable); with floating hose, hawser and SOV.
- Setup B3: Buoy B (including mooring and seabed cable); with floating hose and Software-In-the-Loop SOV.
- Setup C1: Buoy C only (including mooring and seabed cable), without floating hose and SOV.
- Setup C2: Buoy C (including mooring and seabed cable); with floating hose, hawser and SOV.
- Setup C3: Buoy C (including mooring and seabed cable); with floating hose and Software-In-the-Loop SOV and MultiCat.

3.2.1 Wave calibration

Prior to the tests the waves conditions were calibrated without the models in the basin. Wave probes were positioned at the design position of the models (WAVE CL, WAVE C, WAVE B); these wave probes were removed during the tests. A reference wave probe (WAVE 180) was installed aside of the model; these remained in the basin during the tests. In addition the stroke of the wave maker was logged for reference. The wave probe setup during calibration is shown in Figure 4.

3.2.2 Setup B1: Buoy B only

This setup allows to evaluate the behaviour of Buoy B and its mooring system (Test objectives 1, 3) in 1yr, 10yr and 100yr return wave conditions. A schematic overview of this test setup is shown in Figure 12.

The setup consists of:

- Buoy B
- Mooring system B consisting of six mooring lines
- Seabed cable B

The setup was applied to perform the following tests:

- Static offset tests
- Hydrostatic inclination tests
- Free-floating decay tests
- Moored decay tests
- Tests in 1yr, 10yr and 100yr wave conditions

3.2.3 Setup B2: Buoy B with floating hose, hawser and 104 m SOV model

This setup allows to select the appropriate floating hose length and determine the loads in the hawser.

- Tests were performed with the SOV kept in position by soft mooring to determine the appropriate floating hose length.
- Tests were performed with the SOV kept aligned by the hawser and Backward Pull to evaluate the loads in the hawser.

The setup consists of:

- Buoy B
- Mooring system B consisting of six mooring lines
- Seabed cable B
- 104 m SOV model
- Floating hose B with 30, 40, 50 m length
- Hawser B, Hawser B ALTERNATIVE

A schematic overview of this setup is shown in Figure 13.

The setup was applied to perform the following tests:

- Tests in operational wave conditions: H_S = 2.5, 3.5, 4.0 m
- Tests with various floating hose lengths: 30, 40, 50 m
- Tests with 10 t and 15 t Backward Pull (BP) by the SOV
- Tests with various hawser alternatives; Hawser B, Hawser B + 25 m, Hawser B ALTERNATIVE

3.2.4 Setup B3: Buoy B with floating hose and SIL SOV

This setup allows to evaluate the behaviour of Buoy B in combination with the hawser loads by the SIL SOV model. The SIL SOV model consists of a numerical representation of a 104 m SOV including: wave loads (based on the actual wave train in the basin), current loads, wind loads, Backward Pull. The SIL model returns mean, low frequency and wave frequency loads.

The setup consists of:

- Buoy B
- Mooring system B consisting of six mooring lines
- Seabed cable B
- 104 m SIL SOV model
- Hawser B

The physical SOV model and floating hose were present in the setup for visual purposes only. No significant mechanical interactions (only the floating hose) between the physical SOV and buoy were present.

A schematic overview of this setup is shown in Figure 14.

3.2.5 Setup C1: Buoy C only

This setup allows to evaluate the behaviour of Buoy C and its mooring system in operational (H_S = 1.0 m) and maximum (1yr summer) wave conditions. A schematic overview of this test setup is shown in Figure 15.

The setup consists of:

- Buoy C

- Mooring system C consisting of three mooring lines
- Seabed cable B

The setup was applied to perform the following tests:

- Static offset tests
- Hydrostatic inclination tests
- Free-floating decay tests
- Moored decay tests
- Tests in H_S = 1.0 m and 1yr summer wave conditions

3.2.6 Setup C2: with floating hose, hawser and 44 m SOV model

This setup allows to select the appropriate floating hose length and determine the loads in the hawser.

- Tests were performed with the SOV kept in position by soft mooring to determine the appropriate floating hose length.
- Tests were performed with the SOV kept aligned by the hawser and Backward Pull to evaluate the loads in the hawser.

The setup consists of:

- Buoy C
- Mooring system C consisting of three mooring lines
- Seabed cable B
- 44 m SOV model
- Floating hose C with 30, 32.5, 35, 40 m length
- Hawser C

A schematic overview of this setup is shown in Figure 16.

The setup was applied to perform the following tests:

- Tests in operational and maximum wave conditions: H_S = 1.0, 2.9 m
- Tests with various floating hose lengths: 30, 32.5, 35, 40 m length
- Tests with 0, 1, 2 t Backward Pull (BP) by the SOV

3.2.7 Setup C3: Buoy C with floating hose and SIL SOV

This setup allows to evaluate the behaviour of Buoy C in combination with the hawser loads by the SIL model. The SIL model consists of a numerical representations of:

- 44 m SOV including: wave loads (based on the actual wave train in the basin), current loads, wind loads, Backward Pull or Dynamic Positioning (DP).
- 35 m MultiCat including: wave loads (based on the actual wave train in the basin), current loads, wind loads, Backward Pull (1 t).

The SIL model returns mean, low frequency and wave frequency loads.

The setup consists of:

- Buoy C
- Mooring system C consisting of three mooring lines
- Seabed cable B
- 44 m SIL SOV model / 35 m SIL MultiCat Model
- Hawser B

The physical SOV model and floating hose were present in the setup for visual purposes only. No significant mechanical interactions (only the floating hose) between the physical SOV and buoy were present.

A schematic overview of this setup is shown in Figure 17.

3.3 Soft mooring setup

During the tests, a so-called soft spring mooring system is used to keep the SOV model on position and at the specified heading with respect to the waves.
The soft mooring system consists of four horizontal steel lines including linear springs. All four soft mooring lines are identical to avoid undesired coupling effects between modes of motion. The four lines of the soft mooring system are oriented horizontally at the waterline between the floater and four mooring points in the basin.
Overviews of the soft mooring setups applied during the test programme including fairlead locations are given in Figure 3 and Figure 9.

The linearised stiffness of the soft mooring system in surge (C_{xx}), sway (C_{yy}) and yaw ($C_{\psi\psi}$) is computed with the following formulas:

$$C_{xx} = \sum_{i=1}^{4} \frac{T_{0_i}}{L_{0_i}} \cdot \sin^2 \alpha_i + c_i \cos^2 \alpha_i$$

$$C_{yy} = \sum_{i=1}^{4} \frac{T_{0_i}}{L_{0_i}} \cdot \cos^2 \alpha_i + c_i \sin^2 \alpha_i$$

$$C_{\psi\psi} = \sum_{i=1}^{4} c_i L_{m_i}^2 \cdot \sin\left(\alpha_i - \beta_i\right)^2 + T_{0_i} \cdot L_{m_i} \cdot \cos\left(\alpha_i - \beta_i\right) + T_{0_i} \cdot \frac{L_{m_i}^2}{L_{0_i}} \cdot \left(1 - \sin\left(\alpha_i - \beta_i\right)^2\right)$$

In which:

α_i = angle of the soft mooring lines w.r.t. the travelling direction of the wave [= 45 deg]
c_i = Stiffness of line i [scale 11.0: 8.1 kN/m; scale 25.77: 44.5 kN/m]
β_i = Orientation of the fairlead (0 deg or 180 deg)[deg]
$L0_i$ = Stretched length of line i in equilibrium position, see Figure 3 and Figure 9.
Lm_i = Distance of CL to fairlead, see Figure 3 and Figure 9.
$T0_i$ = Pretension in line i [scale 11.0: 100 kN; scale 25.77: 1291 kN]

This results in a mooring system with the following theoretical horizontal stiffness and approx. natural periods for the soft mooring system:

Mode	Scale 11.0		Scale 25.77	
	Stiffness [kN/m, kNm/rad]	Natural period [s]	Stiffness [kN/m, kNm/rad]	Natural period [s]
Surge	20.5	156.2	112.7	66.7
Sway	20.5	156.2	112.7	66.7
Yaw	5.5E+4	78.1	3.0E+5	33.3

These natural periods are outside the wave energy regime, therefore no response at these natural periods due to wave loads are expected.

3.4 Model components Buoy B

Buoy B and its associated components are represented on scale 1:25.77.

3.4.1 Buoy B geometry

Buoy B has a diameter of 8.2 m. The geometry of Buoy B is specified in Provided Information [3]. This drawing represents a buoy with 10.5 m diameter and is scaled by 80% to represent Buoy B with D = 8.2 m.

The Buoy B model (Model No. 10368) was built at a geometric scale ratio of 1 to 25.77. The model components for Buoy B consist of:

- Buoy B hull.
- Appurtenances: skirt, boatlanding, charging hose and hawser guidance structures.
- A swivel to allow weathervaning between the buoy and its mooring.
- Spider to support the six mooring lines.
- The deckhouse and hull are fully closed, no water can enter.

The model was built of PVC with 3D printed appurtenances. The geometry is shown in Figure 1. Impressions of the model are given on Photo 1 and Photo 2.

The instrumentation installed on Buoy B is shown in Figure 2 and consists of:

- NDI Target to measure 6DOF motion
- Hang-off loads at the six mooring lines, seabed cable, floating hose and hawser

The weight distribution is specified by Provided Information [5]. The specified weight distribution did not contain displacement of the appurtenances. The realised displacement, including appurtenances, is somewhat larger. The realised mass is increased accordingly. The realised inertia (I) is kept according to specifications, as a result the presented radii of inertia (k) are smaller. The realised weight distribution is listed in Table 2.

3.4.2 Mooring system B

The mooring system of Buoy B is specified in Provided Information [1] and summarised in Table 16. The associated specified water depth is 20 m. In the model tests Buoy B was installed in 25.77 m water depth. Furthermore the lengths of the leeward lines are reduced to fit in the basin floor.

The model mooring system is designed such to match the horizontal stiffness characteristics of the specified mooring system. The model mooring system is designed in accordance to Ref. [3]. MARIN's static mooring analysis software aNyMOOR is used. aNyMOOR applies imposed offsets and returns the static mooring restoring force.

For the present project the mooring lines are truncated as follows:

1) Reduce length of lines 2-6 to fit within basin width
2) Adjust water depth (25.77 m) to model test setup
3) Adjust line properties to standard available chain
4) Include spring to represent EA
5) Adjust pretensions to match vertical pretension Fz_moor of 22,852 kg

The model mooring system properties are listed in Table 17.

The restoring force characteristics of the truncated mooring system design are presented in Figure 18 in combination with the specified restoring force characteristics and with the measured characteristics after installation of the system in the basin. The characteristics of the specified, truncated and measured systems show the following:

- The truncated mooring system design is more stiff than the specified design. This is inevitable due to the truncated line length of wave ward lines 2 and 6 and associated deviations in geometry and restoring forces.

3.4.3 Seabed cable B

The properties of the seabed cable are given in Provided Information [8]. The seabed cable consists of a bend stiffener at the buoy, the cable and buoyancy floaters.
On model scale the bend stiffener is not modelled. The cable and floaters are made of standard available materials. The following approach is followed:

1) The diameter and submerged weight of the cable and floater section are modelled as close as possible by a steel cable integrated in a silicon hose.
2) The bending stiffness is a factor 110 too high, while the bend stiffener is not modelled.
3) The floaters are made of light weight foam. This defines their mass.
4) Floater geometry adjusted for manufacturability. This defines their buoyancy.
5) Number of floaters is adjusted to obtain the Total submerged weight.
6) Floaters will be distributed over specified section length.

The properties of the seabed cable are listed in Table 23.

3.4.4 Hawser B and B ALTERNATIVE

The properties of the hawser are given in Provided Information [8] and summarised in Table 20.
The model hawser is made of a steel wire. A bi-linear spring is included to represent the non-linear stiffness characteristics. The properties of the model hawser are listed Table 20 in as well.

3.4.5 Floating hose B

The floating charging hose is represented by a silicon hose. An available stock silicon hose is selected to match the bending stiffness, submerged weight and diameter of the hose as close as possible. The length of the hose B is varied during the tests between 30 and 50 m. Markers are added for visual tracking of the hose.

The properties of the floating are provided by Provided Information [7] and summarised in Table 22.
The properties of the model floating hose are listed in Table 22 as well.

3.5 Model components Buoy C

Buoy C and its associated components are represented on scale 1:11.0.

3.5.1 Buoy C geometry

The geometry of Buoy C is specified in Provided Information [4]. The diameter of Buoy C is 3.5 m.

The Buoy C model (Model No. 10369) was built at a geometric scale ratio of 1 to 11.0. The model components for Buoy C consist of:

- Buoy C hull.
- Appurtenances: skirt and floating hose guidance structures.
- A swivel to allow weathervaning between the buoy and its mooring.
- Spider to support the three mooring lines.
- The ballast pull-in-pull-out mechanism of the charging hose is not represented.
- Deckhouse with opening at the charging cable entrance; flush pipe for water to leave the turret; no rat holes.

The model was built of PVC with 3D printed appurtenances. The geometry is shown in Figure 7. Impressions of the model are given on Photo 3 and Photo 4.

The instrumentation installed on Buoy C is shown in Figure 8 and consists of:

- NDI Target to measure 6DOF motion.
- Three wave probes: one inside the deckhouse, two outside.
- Hang-off loads at the three mooring lines, seabed cable, floating hose and hawser.

The weight distribution is specified by Provided Information [6]. The specified weight distribution did not contain displacement of the appurtenances. The realised displacement, including appurtenances, is somewhat larger. The realised mass is increased accordingly. The realised inertia (I) is kept according to specifications, as a result the presented radii of inertia (k) are smaller. The realised weight distribution is listed in Table 3.

3.5.2 Mooring system C

The mooring system of Buoy C is specified in Provided Information [2] and summarised in Table 18. The associated specified water depth is 20 m. In the model tests Buoy C is installed in 11.0 m water depth. Furthermore the lengths of the leeward lines are reduced to fit in the basin floor.

The model mooring system is designed such to match the horizontal stiffness characteristics of the specified mooring system. The model mooring system is designed in accordance to Ref. [3]. MARINs static mooring analysis software aNyMOOR is used. aNyMOOR applies imposed offsets and returns the static mooring restoring force.

For the present project the mooring lines are truncated as follows:

1) Reduce length of lines 2 and 3 to fit within basin width
2) Adjust water depth (11.0 m) to model test setup
3) Adjust line properties to standard available chain
4) Include spring to represent EA
5) Adjust pretensions to match vertical pretension Fz_moor of 2,250 kg

The model mooring system properties are listed in Table 19.

The restoring force characteristics of the truncated mooring system design are presented in Figure 19 in combination with the specified restoring force characteristics and with the measured characteristics after installation of the system in the basin. The characteristics of the specified, truncated and measured systems show the following:

- For offsets ranging till x = -3.5 m the characteristics show a good agreement.
- For offsets larger than x < -3.5 m the truncated system is more stiff than the specified system.

3.5.3 Hawser C

The properties of the hawser are given in Provided Information [8] and summarised in Table 21.
The model hawser is made of a steel wire. A bi-linear spring is included to represent the non-linear stiffness characteristics. The properties of the model hawser are listed Table 21 in as well.

3.5.4 Floating hose C

The floating charging hose is represented by a silicon hose. A stock available silicon hose is selected to match the bending stiffness, submerged weight and diameter of the hose as close as possible. The length of the hose C is varied during the tests between 30 and 40 m. Markers are added for visual tracking of the hose.

The properties of the floating are provided by Provided Information [7] and summarised in Table 22.
The properties of the model floating hose are listed in Table 22 as well.

3.6 SOV

The bunkering vessel applied in the tests consists of MARINs stock SOV model. The particulars of the SOV are given in Table 9.

During some of the tests the SOV was kept in position by the soft mooring system ,see Section 3.3.
During other tests the SOV was aligned with the hawser and delivering Backward Pull. The Backward Pull loads by the SOV were generated by a wire and pulley system, positioned at an earth fixed position behind the SOV.

3.7 Digital Twin & Software-In-the-Loop modelling

For a selection of tests (B3 and C3) use was made of a so-called Software-In-the-Loop (SIL) approach. The SIL approach consists of Digital Twins of the SOV and MultiCat and a dynamic winch as interface between the numerical models and the physical basin.

The Digital Twins are numerical time domain simulation models of the SOV and MultiCat, represented in MARINs in-house time domain simulation software aNySIM-xmf.

The execution of the time domain simulations is synchronised with the basin. The numerical model is initialised based on the activity of the wave maker. The communication time step between the basin and XMF is 10 Hz model scale. Every communication time step the position of the buoy is forwarded from the basin to XMF, XMF calculates the actions of the SOV and returns the load on the hawser to be applied by the winch.

3.7.1 Numerical SOV and MultiCat models

The following properties are represented by the Digital Twin models:

Table 3-1: Properties represented by the Digital Twin models of the SOV and MultiCat

Property	**SOV**	**MultiCat**
Main particulars	Table 9	Table 4
First order wave loads	Diffraction analysis *33350_SOV_44m.hyd* *33350_SOV_103m.hyd*	Diffraction analysis *MARIN_MultiCat_diffraction.hyd*
Second order wave loads		
Current loads	Table 12	Table 7
Wind loads	Table 13	Table 8
Thruster layout and properties	Table 10	Table 5
Bollard Pull	Buoy B tests: 10, 15t Buoy C tests: 1(, 5, 10)t	Buoy B tests: N/A Buoy C tests: 1t
Dynamic Positioning	Table 11	N/A

4 SIMULATION OF ENVIRONMENTAL CONDITIONS

4.1 General

The environmental conditions generated in the Shallow Water Basin are presented in this chapter. Furthermore, the procedures to calibrate the environmental conditions are described. A general description of the wave generation capabilities of the Shallow Water can be found in Appendix F06.

Prior to the model tests the waves were calibrated by measurements at the design position of the model (without the vessel present in the basin). During the calibration and model tests, the waves were monitored at the reference positions.

4.2 Water depth

The water depth in the Shallow Water Basin is 1.0 m on model scale. This water depth represents 11.0 m for Buoy C and 25.77 m for Buoy B.

4.3 Current

Current is not generated in the Shallow Water Basin. The contribution for current is considered to be of limited relevance for operational conditions for the buoys. For the operational conditions tests will be performed for the maximum wave conditions. Based on the metocean data current associated with the maximum wave conditions is 0.5 m/s.

Current loads on the bunkering vessels are taken into account in the numerical SIL model.

4.4 Wind

Wind can not be modelled in the Shallow Water Basin.

Wind loads on the bunkering vessels are taken into account in the numerical SIL model.

4.5 Waves

Uni directional waves are generated in the basin. Waves can be generated up to approx. H_S = 0.27 m on model scale. Detailed capabilities of the wave maker are shown in Appendix F06.

4.5.1 Irregular wave conditions

The irregular wave conditions are selected from Provided Information [9], see also Table 14. The selected conditions are listed in Table 15 and summarised as follows.

- Buoy C:
  - 1yr summer return condition
  - Operational condition: H_S = 1.0 m, T_P = 5.0 s
- Buoy B:
  - 100yr, 10yr, 1yr return conditions
  - Operational conditions: H_S = 4.0 m, 3.5 m, 2.5 m

Realised wave results are available on the FTP. The spectral parameters of the realised waves are summarised in Table 27. The spectra and distributions of the crests and throughs of the Buoy B 100yr wave conditions are shown in Figure 20. These results show:

- The H_S and T_P of the realised waves are within 10% of the target waves; for most cases the accuracy is within 5% of the target values.
- Low frequent energy below 0.05 rad/s (above 125 s) can be observed. This is due to low frequent reflections in the basin, which are not well damped by the beaches.
- The spectra and distribution functions of the Buoy B 100yr wave conditions show a good agreement, with some difference for the various seeds.

4.5.2 Wave spectrum

The irregular seas were adjusted such that the spectral density distribution corresponds with the required theoretical energy distribution at the design position of the model in the basin. The wave spectra used throughout the tests were JONSWAP wave spectra. The JONSWAP spectra are formulated as follows:

$$S_\zeta(\omega) = \frac{C \cdot H_s^2 \cdot \omega_p^4}{\omega^5} \cdot \exp\left(-1.25 \cdot \frac{\omega_p^4}{\omega^4}\right) \cdot \gamma^{\exp\left(-\left(\frac{\omega-\omega_p}{\omega_p \cdot \sigma \cdot \sqrt{2}}\right)^2\right)}$$

with

$$C \cong \frac{0.597 + 0.3125 \cdot \gamma}{1.27 + 1.47 \cdot \gamma + 0.168 \cdot \gamma^2}$$

in which

$S_\zeta(\omega)$ = spectral density at wave frequency ω, [m^2 s]
ω = circular wave frequency, [rad/s]
ω_p = peak frequency = $2\pi/T_P$, [rad/s]
T_P = peak period, [s]
H_s = significant wave height, [m]
γ = peak enhancement factor

and $\sigma = \begin{bmatrix} \sigma_a \text{ for } \omega \le \omega_p \\ \sigma_b \text{ for } \omega > \omega_p \end{bmatrix}$ or $\sigma = \begin{bmatrix} \sigma_a \text{ for } T \ge T_P \\ \sigma_b \text{ for } T < T_P \end{bmatrix}$

The dimensionless shape parameters σ_a and σ_b were taken as:

σ_a = 0.07
σ_b = 0.09

The significant wave height is defined as: $H_S = 4 \cdot \sqrt{\int_0^\infty S_\zeta(\omega)d\omega} = 4 \cdot \sqrt{m_{\zeta 0}}$

where $\sqrt{m_{\zeta 0}}$ is the area beneath the wave spectrum.

4.5.3 Regular wave conditions

Regular waves with wave height (H2a) equal to the design maximum wave height (Hmax) and wave period (T) equal to the peak period (T_P) are calibrated as well. The target and realised wave parameters are listed in Table 27. These results show that the realised wave heights are approx. 10% lower than specified. The realised regular waves are shown in Figure 21.
The maximum wave height associated with the 100yr condition for Buoy B is beyond the wave breaking limit and capacity of the wave makers. Therefor this wave height is reduced from H2a = 12.4 m to H2a = 7.38 m. However, still this wave condition results in a very non-linear sea state with continuous breaking and overtopping waves.

4.5.4 Wave calibration procedure

The wave calibration procedure is described in Appendix E04. Note that only the first order wave spectrum can be calibrated. The second order group wave spectrum and the maximum crest amplitudes cannot be calibrated and are a result of the applied wave seed. The waves are calibrated at the design location in the basin by wave probe WAVE_CL. In addition the waves are measured at several reference locations in the basin as shown in Figure 4 and Figure 5.

The measured wave spectra and the group spectra are visualised and available on the FTP and HD.

5 MEASUREMENTS, DATA ACQUISITION AND POST PROCESSING

5.1 General

An overview of the measured signals as well as their definitions and sign conventions is given in this chapter. Furthermore, the applied instrumentation is listed and some key information of the measurement system is given. Finally, an overview of the signals that were derived from the measured signals is given. The location of the model instrumentation is presented in Figure 2, Figure 6, Figure 8 and Figure 10.

5.2 Data acquisition

The model tests were carried out in the Shallow Water Basin, see also Chapter 3. Part of the signals is measured using an analogue system and part of the applied measurement systems has a direct digital output.

For the data acquisition of the analogue signals the MARIN Measurement System (MMS2) was used. Before sampling an on-line anti-aliasing filter was applied. All the signals were sampled and stored at a sampling rate of 200 Hz. The sampling rate of 200 Hz results in prototype scale time intervals of 0.017 seconds (Buoy C, scale 1:11) and 0.025 seconds (Buoy B, scale 1:25.77) between each two subsequent samples.

The digital signals were measured with the MSES system. For the digital signals no on-line filtering and sampling is required. The digital signals included the measured displacements from the optical measurement systems and the logging of system feedback signals. The applied sampling rate for the digital signals was 100 Hz.

The majority of irregular wave tests, where the focus was on low and wave frequency buoy response, had a duration of ½ + 3 hours each (prototype values). For cases focussing on first order wave force on the floating hose a reduced test duration was used of ½ + 1 hour (prototype values). The first half hour of the measurement is considered as start-up time to let possible transient phenomena vanish. The number of data points are available for the statistical analysis of each measured channel varies based on sample rate, scale and test length. This is shown in Table 5-1 after removal of the start-up time. Note Table 5-1 is for a 100 Hz signal, for signals at 200 Hz the number of available data points is double those shown. For the 3-hour measurements, this is assumed to be sufficient to allow a reliable statistical analysis on the desired parameters, i.e. low and wave frequency phenomena for 3-hour tests and first order wave forces on the floating hose in the 1-hour tests.

Table 5-1: Number of data points for statistical analysis after removal of start up time (at 100 Hz)

Test duration (prototype scale)	1 hour	3 hour
Buoy B – scale 1:25.77	70,916	212,749
Buoy C – scale 11	108,544	325,632

5.3 Instrumentation / measured quantities

This section summarises the instrumentation that was installed in the basin and on the model during the test campaign. The following signals were measured and recorded at a sampling frequency of 100 Hz or 200 Hz:

- *Reference wave heights*
  Resistance type wave probe.

- *Translations (X, Y, Z) and rotations (ϕ, θ, ψ) of the buoys and SOV*
  NDI contact-less optical position measurement system (above water). The system determines the model motions based on the recorded positions of three infrared LEDs on a position target placed on the model. Based on the measured motions of the three LEDs the NDI system calculates the 6 degrees of freedom (3 translations and 3 rotations). All motions are defined in the basin-fixed (BF) system of axes, except roll and pitch which are defined in the ship-fixed (SF) system of axes.
- *Accelerations on the SOV*
  3DOF Piezo-type accelerometers at four locations. This configuration allows to calculate the accelerations in 6DOF at any required position on board of the model.
- *Relative wave heights along the model (buoy C only)*
  Resistance type wave probe.
- *Soft-mooring loads*
  Ring-shaped strain gauge force transducers placed in each line at fairlead position.
- *Mooring line tensions*
  Ring-shaped strain gauge force transducers placed in each line at fairlead position.
- *Hawser and seabed cable tension*
  Ring-shaped strain gauge force transducer

Table 25 represent a list of the measured quantities including their designation, sign conventions and measuring devices. The locations of the instruments are shown in Figure 2, Figure 6, Figure 8 and Figure 10.

5.4 Derived quantities

In Table 26 a review of the signals derived from the measured signals is presented. The signals that were derived from the measured signals are as follows:

- Accelerations of the *SOV* at CoG (6DOF) and at other points (3DOF).
- Motions of the buoy and SOV at CoG (6DOF) and at other points (3DOF).
- Soft mooring forces and moment (3DOF, Fx, Fy, Mz)

The formulas used to calculate the derived signals are described in Appendix D12. The derived signals include for example the total loads on the soft-mooring, the motions and accelerations at any point of the floater, or the total loads in the force frame.

5.5 Examples of signals in irregular wave tests

The records of the signals during the tests were of one of the following types:

- The type I record consists of a fast oscillating value, of which the frequency corresponds to the frequency of the wave (WF).

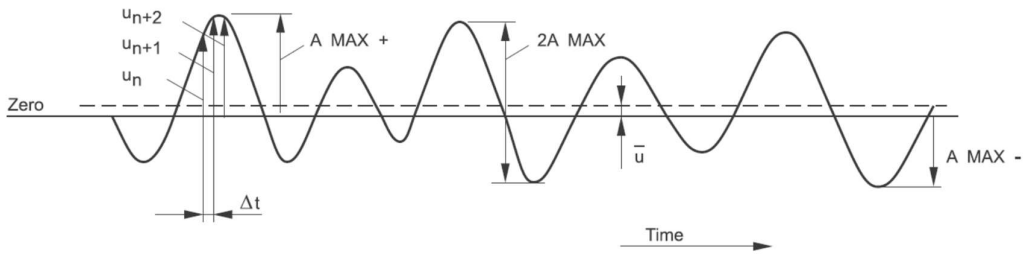


Figure 5-1: Type I signal with WF oscillations

- The type II record consists of a fast oscillating value, which is superimposed on a slowly varying value (LF).

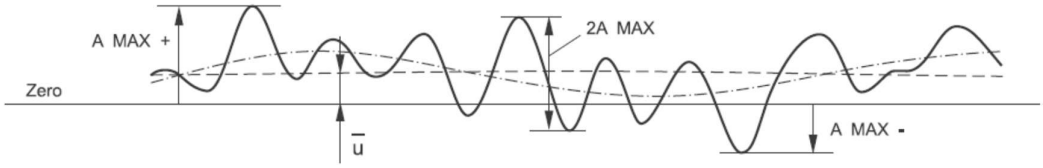


Figure 5-2: Type II signal with combined WF and LF oscillations

- The type III record consists also of an oscillating signal of which the frequency corresponds to the wave frequency, superimposed on a slowly varying signal. But in this case the fast oscillating part is small compared to the slowly varying signal.

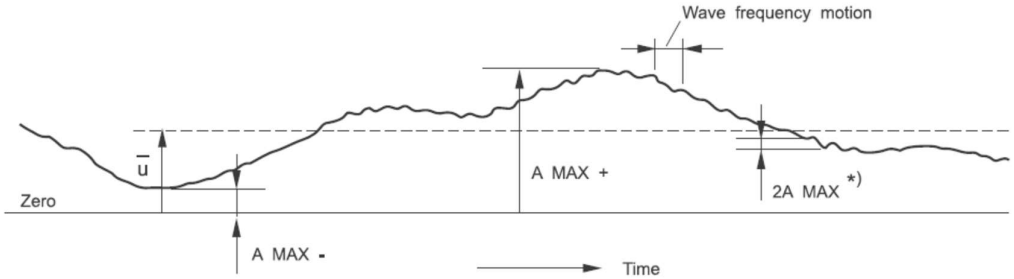


Figure 5-3: Type III signal with LF oscillations

- The type IV record is typical for slamming loads as well as green water on deck.

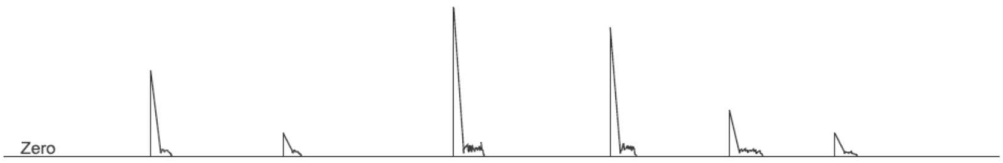


Figure 5-4: Type IV signal for impact loads

5.6 Types of data reduction

Each paragraph of this chapter discusses types of analyses that have been applied to present the model test results.

5.6.1 Statistical analysis

The two types of statistical analysis that can be done on the measured data are described in the Appendix D03 at the end of this report. They are referred to as Statistical and Extrema Statistical analysis later on in this report. For the extrema statistical analysis a low pass filter is used with a cut-off frequency of 3 * wave frequency.

5.6.2 Signal filtering

For all signals except the high-frequent slamming load and pressure measurements, a Low Frequency (LF), Wave Frequency (WF) and High Frequency (HF) filtering, including a statistical analysis was carried out. The boundary of all filter settings are documented in Table 5-2. The Nyquist frequency ω_{NY} is about 61.9 rad/s (scale 1:25.77) and 94.7 rad/s (scale 1:11).

Table 5-2: Filter settings in [rad/s]

Tests	UF	LF	WF
Tests in Waves	0.0 – ω_{NY}	0.0 – 0.3	0.25 – 3.0

5.6.3 Decay Analysis

The decay tests are analysed in order to determine the natural periods and damping coefficients. The method used to analyse the damping coefficients based on a decay test are described in Appendix D01.

5.6.4 Weibull fits

For the extreme values of a number of signals (e.g. roll motion) a 3-parameter Weibull fit was made through 50% of the highest peak or through values. The percentage of peaks to be used for the Weibull fit was selected by MARIN. This fitted line was used to determine the most probable maximum (MPM) values of the signals. A description of this methodology is given in Appendix D03.

5.6.5 Response Spectra

The motion response spectrum was determined for all irregular wave tests. It was analysed at the target position. A mathematical description of irregular phenomena is given in Appendix D02.

5.6.6 Response Amplitude Operator (RAO)

The motion RAO was determined for all wave tests. It was analysed at the target position. The lead signal is the calibrated wave. The theoretical background of the RAO is described in Appendix D06.

5.6.7 Fast Fourier transform (FFT)

Several types of analysis need an FFT, like the response spectra or the filtered extrema statistical analysis. The FFT is always applied on resampled data to avoid issues due to non-equidistant data.

5.7 Data analysis and deliverables for each type of test

5.7.1 Regular wave calibration

Channels:

- WAVE_CL: wave probe at the design position in the basin
- Wave probes at reference positions in the basin, see Figure 4 and Figure 5

Deliverables

- Harmonic Analysis of the measured regular wave
- Statistics of current measurement
- Time traces – plotted and in HDF5 format

Channels:

- Other wave probes
- Stroke of wave flap

Deliverables

- Time traces – plotted and in HDF5 format

5.7.2 Irregular wave calibration

Channels:

- WAVE_CL: wave probe at the design position in the basin
- Wave probes at reference positions in the basin, see Figure 4 and Figure 5

Deliverables

- (Extrema) statistics of measured wave elevation
- Comparison measured vs. specified wave spectrum
- Comparison of measured vs. specified significant wave height H_S
- Comparison of measured vs. specified peak period T_P
- Time traces – H5 format

Channels:

- Other wave probes
- Stroke of wave flap

Deliverables

- Time traces – HDF5 format

5.7.3 Decay Tests

Channels:

- 6DOF motions at CoG

Deliverables:

- PQ analysis
- Time trace plot of measured quantity (for example, roll for a roll decay) combined with a fit based on the derived PQ values
- Time traces – plotted and in HDF5 format

5.7.4 Model Tests in Regular Waves

Channels:

- Reference basin wave elevations
- 6DOF motions at COG and at other points (3DOF)
- Seabed cable force
- Buoy mooring line tensions
- Stroke of wave flap

Deliverables:

- Time traces of the measured quantities – HDF5 format
- Harmonic Analyse of all relevant signals for the same time frame as selected for the wave calibration

5.7.5 Model Tests in Irregular Waves

Channels:

- Reference basin wave elevations
- 6DOF motions at COG and at other points (3DOF)
- 3DOF angular accelerations at the CoG for SOV

- 3DOF accelerations at CoG and other points
- Relative wave elevations (buoy C)
- Horizontal loads applied on the SOV by the mooring arrangement
- Buoy mooring line tensions
- Seabed cable force
- Floating hose load
- Hawser load
- Stroke of wave flap

Deliverables:

- Time trace plots of the unfiltered measured quantities
- Time traces of the unfiltered measured quantities – HDF5 format
- Time traces of the filtered measured quantities (LF+WF) – HDF5 format
- (Extrema) Statistical mean crossing statistical analysis of unfiltered signals (UF)
- (Extrema) Statistical mean crossing statistical analysis of filtered signals (LF+WF)
- Power Spectrum Density (PSD) plots and tables (HDF5 format) of relevant signals
- Response Amplitude Operator RAO plots and tables (HDF5 format) of relevant signals
- Weibull Analysis for relevant signals
- Summary of the troughs and peaks - HDF5 format
- Weibull distribution plots and tables (cvs format) for relevant signals

5.7.6 Static Loads of the mooring system

Channels:

- Mooring line tensions
- Static offset of buoy from design position

Deliverables:

- Statistics
- Plot offset curves

5.8 Visualisation

During the model tests and the preparations still photographs were taken. Furthermore, video recordings were made

Still photographs

Still photographs were taken of the models in the workshop, the test set-up in the basin and during a selected number of model tests. A selection of the photographs is shown on the photo pages at the end of this report.

Video recordings

Video recordings were made to obtain a good overall impression of the behaviour of the floaters. Three above water video cameras were used for the wave tests.

6 TEST REVIEW AND EXPERIMENTAL PROCEDURES

6.1 Test review

In this section, a brief overview of the model tests performed is given. A complete overview of the test matrix is given in Table 27 through Table 29.

- The overall model test programme included the following series of tests:
  - Wave calibrations without the models in the basin.
  - Setup B1: Buoy B only (including mooring and seabed cable), without floating hose and SOV
    - Static offset tests
    - Hydrostatic inclination tests
    - Free-floating decay tests
    - Moored decay tests
    - Tests in 1yr, 10yr and 100yr wave conditions
  - Setup B2: Buoy B (including mooring and seabed cable); with floating hose and SOV
    - Tests in operational wave conditions
  - Setup B3: Buoy B (including mooring and seabed cable); with floating hose and Software-In-the Loop SOV
    - Tests in operational wave conditions; SOV/ MultiCat including DP, current, wind and waves by Software-In-the-Loop modelling
  - Setup C1: Buoy C only (including mooring and seabed cable), without floating hose and SOV
    - Static offset tests
    - Hydrostatic inclination tests
    - Free-floating decay tests
    - Moored decay tests
    - Tests in 1yr and operational wave conditions
  - Setup C2: Buoy C (including mooring and seabed cable); with floating hose and SOV
    - Tests in 1yr and operational wave conditions
  - Setup C3: Buoy C (including mooring and seabed cable); with floating hose and Software-In-the-Loop SOV and MultiCat
    - Tests in 1yr and operational wave conditions; SOV/ MultiCat including DP, current, wind and waves by Software-In-the-Loop modelling

In addition to the above listed tests decay tests were performed on the SOV free floating and in soft mooring.

6.2 Experimental procedures

The test procedures applied in the different types of model tests performed in this project are described in this section.

6.2.1 Weight distribution procedure

Prior to any test in the basin, the weight distribution of the model is calibrated. The experimental procedure followed to prepare the weight distribution of the model is described in Appendix M05. The calibrated weight distributions are shown in Table 2, Table 3 and Table 9 for Buoy B, C and the SOV respectively.

6.2.2 Inclination tests

Prior to any test in the basin and after calibration of the weight distribution on the Resonic table, inclination tests are conducted to verify the correctness of the roll and pitch stiffness, $GM_{T/L}$ and KG. The inclination tests are performed at free floating draught, without the mooring lines connected. The free floating weight distributions are listed in Table 2 and Table 3. For the inclination tests, one weight located at midship is shifted in the transverse direction, and the resulting inclination roll angle is measured. Based on the shifting distance, shifted mass and displacement of the floater, the GM value is calculated.

6.2.3 Zero adjustment

All results presented in this report are given with respect to the ‘zero values’ taken after each setup change and at the beginning of every new day. In its zero-position, the floater is at the Design Position at the specified draught and at even keel. The zero values in each test represent the actual values of the respective quantities for the model in this starting position.

6.2.4 Wave calibration

Both regular and irregular waves were calibrated in the basin prior to the start of the model tests. The experimental procedure followed to calibrate waves is described in Appendix E04. Note only the sea state spectrum is calibrated. The low frequent group wave spectrum and (maximum) crest heights are not calibrated and are a result of the random seed variation.

6.2.5 Static load tests

Prior to the actual wave model tests, the stiffness of the mooring arrangement was verified by means of imposed offset tests, also referred to as static load tests. The experimental procedure followed to carry out the static load tests is described in Appendix P02. Only the mooring line loads at the fairlead were measured during this campaign. The overall mooring restoring loads were not measured.

6.2.6 Decay tests

Motion decay tests are carried out by pulling or pushing the model from its equilibrium position, after which it is released. In this project, decay tests were carried out for all degrees of freedom. The resulting decaying motions are recorded for later analysis. The experimental test procedure followed to carry out the decay tests is described in Appendix P03.

6.2.7 Tests in waves

The procedure followed to execute the tests in waves is described in Appendix P04 at the end of this report.

6.2.8 Software-In-the-Loop tests

The tests with the bunkering vessels represented by a Digital Twin in XMF and the SIL model were performed as follows:

The following preparations were performed prior to the tests:

- Wave splitting analysis is performed for each calibrated wave time series. Wave spitting analysis results in a spectral distribution of the wave, including amplitude, frequency and phase components of each calibrated wave.
- A specified XMF case is prepared for each test condition. This XMF model contains a representation of the bunkering vessel (SOV or MultiCat) and the hawser. The spectral distribution of the wave is loaded in XMF. Based on this XMF is capable to calculate the propagation of the wave field and determine the local wave elevation at each location and moment in the domain.
- The XMF cases are stored on the computer in the basin controlling the dynamic winch.

The following actions are undertaken during execution of the test programme:

- The hawser is connected to the buoy at the hawser attachment point and to the dynamic winch.
- The dynamic winch is controlled by MARINs Basin Software System (BSS). BSS is controlled by closed control loop (based on the load measured in the hawser) to reduce delays and damping of the winch.
- For each specific test the prepared XMF model is activated prior to the test. The XMF model has status “Initializing”.
- The measurement system and wave system are started as described in the previous section.
- The WAVE_FLAP signal is used to trigger the XMF model. The XMF model has status “Advance”.
- The XMF model status changes to “shut down” once the end time of the calibrated wave time series is reached.

7 RESULTS AND DISCUSSION

7.1 Environmental calibration

The wave conditions are calibrated prior to the tests without the model in the basin. The results of the environmental calibrations are described in Section 4.

7.2 System verification

7.2.1 Hydrostatic verification and weight distribution

The weight distribution was realised as described Appendix M05. Inclination tests, as described in Section 6.2.2. The target and realised weight distributions are listed in Table 2 and Table 3. The displacement and mass of the realised weight distributions are larger than specified, due to the presence of appurtenances, which were not included in the specified weight distribution. The realised inertia (I) is kept according to specifications, as a result the presented radii of inertia (k) are smaller. In general the specified and realised weight distributions show a good agreement.

7.2.2 Mooring verification

The results of the realised mooring system versus the mooring system design and specified system are described in Sections 3.4.2 and 3.5.2. In general the realised mooring systems are somewhat more stiff than the specified systems.

7.3 Natural periods and damping values

The results of all decay tests performed are summarised in Table 33. Natural periods and damping (linear and quadratic) are presented in Figure 22 and Figure 23. The results presented in these figures show:

- Natural periods of roll and pitch decrease due to the additional stiffness of the mooring system. The influence of the mooring system on the heave natural period is small.
- Heave, roll and pitch damping of the free floating buoys is mainly linear. The mooring system results in a quadratic contribution as well.

From the measured natural periods, known stiffness and mass, the unknown added mass can be derived by:

$$T = 2\pi\sqrt{\frac{\mathrm{m} + \mathrm{a}}{c}}$$

The added mass derived from the free floating decay tests is listed in the table below.

Table 7-1: Added mass derived from free floating decay tests

TestID	mode	Period [s]	a [t, tm2]	a/m [%]
33350_03BT_03_001_004_01	ROLL_BUOY [deg]	10.09	1325	112%
33350_03BT_03_001_005_01	PITCH_BUOY [deg]	8.87	756	64%
33350_03BT_03_001_006_01	Z_COG_BUOY [m]	5.37	271	219%
33350_03BT_05_001_003_01	ROLL_BUOY [deg]	6.23	10	47%
33350_03BT_05_001_004_01	PITCH_BUOY [deg]	6.44	12	56%
33350_03BT_05_001_005_01	Z_COG_BUOY [m]	3.65	24	278%

7.4 Extreme events

The mean, standard deviation, minimum and maximum motions, mooring and hawser loads and relative wave heights are listed in Table 30 through Table 32. The results presented in these tables show the following:

- Buoy motions
  - In Buoy only tests (Setups B1 and C1) the buoys are free to weathervane. In general the buoys weathervane such that the appurtenances are at the leeward side of the buoys. For Buoy B this results in a mean orientation of approx. 90°, for Buoy C approx. - 70°. Note roll and pitch motions are Ship-Fixed, while X, Y and Z motions are Earth-Fixed. In some cases the buoys rotate 360°. Some rotations occur rapidly due to extreme wave events and asymmetry first order yaw loading. Other rotations are slow due to asymmetric wave drift loading. Examples of large yawing motions are shown in Figure 24.
    In test 05_004_003_05, being the 1yr summer storm condition for Buoy C only (Setup C1) rapid change of yaw occurs followed by large roll and pitch motions, see Figure 25. The large roll and pitch motions originate from several high steep waves after each other. Note roll and pitch motions are given in the Ship-Fixed coordinate system.
  - In tests with the hawser attached at the leeward side (i.e. stern of the buoys) the buoys SF coordinate systems align with the EF coordinate system at approx. 0° heading.

- Mooring line and hawser loads:
  - Negative tension in the mooring lines is registered in some cases during slack line events. This is considered to be part of the measurement uncertainty due to the sensor accuracy and zeroing procedure. The actual tension can be considered 0 kN.
  - For Buoy B the maximum mooring line loads occur in the wave ward line 1 during 100yr storm conditions. The maxima and MPM (50%) loads are shown in Figure 27. Snap loads in mooring lines 1 and 4 are observed in these conditions, see Figure 27. The maximum measured load is 1930kN and MPM (50% peaks) 1786 kN. The event of maximum load in the mooring line occurs during test 03_004_082_001 at t = 7072 s and is shown in Figure 26 and Photo 6. This event shows the following behaviour of the buoy:
    - A steep breaking wave overtops the buoy completely and gives it a horizontal setback of approx. -3.1 m. The peak load of 1930 kN occurs in line 1 due to the horizontal setback.
    - When the wave has passed the buoy restores to x = +3.5 m. This results in slack of wave ward mooring line 1 and a peak load of leeward mooring line 4. The skirt and underside of the buoy come out the water, slamming occurs.
  - High loads are found in leeward line 4, see Figure 27. This is due to snap loads in this mooring line. Snap loads in the leeward line occur due to severe pitch motions of the buoy, after which the mooring line tension drops to 0 kN and increases rapidly afterwards. The maxima and MPM (50%) loads are shown in Figure 28. The maximum measured load is 1426 kN and MPM (50% peaks) 1447 kN.
  - For Buoy C the maximum mooring line loads in the wave ward line 1 are approx. 250 kN and occur in the 1yr summer storm condition with the SIL SOV and MultiCat attached and delivering 1 t BP. The maximum load in the hawser are 190 kN with the SIL SOV and 172 kN with the SIL MultiCat.

- Relative wave heights:
  - REL_01 shows waves are exceeding main deck (z = 1.85 m) several times. REL_02 (starting z = 2.33 m above keel, height 0.75 m, hose opening at 0.4 m) and REL_03 (inside the deckhouse) show water has entered the deckhouse through the hose opening in 1yr summer storm conditions during several extreme event of waves overtopping the buoy and incidentally in operational conditions (H_S = 1.0 m) due to large SOV loads on the hawser and related pitch of the buoy. Photo 7 gives an impression of such events.

The behaviour during such events of steep and breaking waves overtopping the buoys is described above: water overtopping the buoys, high mooring line loads in the wave ward lines, slack mooring lines and slamming on the skirt occur.

7.5 Response Buoy C

7.5.1 Buoy C

PSDs & RAOs of the motions of Buoy C alone (Setup C1) and with the SOV present, but no hawser attached (Setup C2) are presented in Figure 30 for the operational (H_S = 1.0 m) and 1yr summer storm (H_S = 2.9 m) conditions. The RAOs presented in these figures show in general a good agreement, indicating mainly linear response for sea states in this range.
PSDs & RAOs of the motions of Buoy C alone (Setup C1) and with the SOV and hawser attached (Setups C2 and C3) are presented in Figure 31. The results in these figures show the attachment of the hawser has large influence on the motions of the buoy. The following can be observed:

- The hawser adds low frequent motion response to the buoy, mainly for the modes of motion in-line with the waves and SOV: surge and pitch. For the Buoy C only cases the low frequent motions are marginal, with the hawser attached these become significant as well.
- The buoy follows the low frequent behaviour induced by the presence of the SOV and the double mass spring system.
- The pitch RAOs from Setups C2 and C3 follow the hawser load RAOs. This demonstrates that the buoy motions are dominated by the hawser loads, especially pitch.

7.5.2 SOV

Figure 32 shows PSDs & RAOs of the motions of the SOV from the tests with the hawser and BP (Setup C2) and in soft mooring (Setup C3). RAOs from diffraction analysis (green: 180° wave direction; red: 175° wave direction) are added in this figure as well. The results presented in this figure show:

- Low frequent motions of the SOV occur due to double mass spring system setup.
  - Surge motions are predominantly low frequent.
  - Low frequent motions for Setup C2 are larger than for Setup C3. Note in Setup C2 the SOV is kept in position by the hawser and the BP load, while in Setup C3 the SOV is kept in position by the soft mooring system, while the hawser load is applied by the SIL system.
- In general the RAOs show a good agreement. Surge, heave and pitch are represented according to expectations from diffraction analysis. Sway, roll and yaw are marginal and correspond to calculated RAOs for small off the bow angles (red: 175° wave direction).
- Distinct peaks can be observed on the measured RAOs. These are considered to be an effect of transverse standing waves in the basin due to the presence of the Buoy and SOV model. In Setup C1 these peaks are less evident on reference wave probe Wave 180, due to the absence of the SOV, see Figure 29; However, they can be observed on the sway buoy motions, see Figure 30.
- The comparison of the RAOs from these tests (Setup C2 and Setup C3) indicates that the influence of the hawser on the motion RAO of the vessel (Setup C2) is marginal.

7.5.3 Effect of Backward Pull

The PSD and RAO of the hawser loads from Setup C2 with 0 t, 1 t and 2 t BP are shown in Figure 34. These figures show the following:

- Low frequent hawser loads, due to low frequent SOV surge motions, can be observed for 1 t and 2 t BP. In case of 0 t BP the low frequent hawser loads are small.

7.5.4 Effect of SIL modelling

PSDs and RAOs of the motions of the buoy under the influence of 1 t physical (Setup C2) and SIL (Setup C3) BP are presented in Figure 35. PSDs and RAOs of the mooring line and hawser loads are presented in Figure 36. The results presented in these figures show:

- The low frequent hawser loads are underestimated by the SIL system.
- The wave frequent hawser loads are overestimated by the SIL system, when the SIL system is programmed to deliver 1 t BP.

7.5.5 Effect of DP system

Several tests in Setup C3 were performed with a DP system activated in the SIL model of the SOV. The objective of the DP system is to eliminate mean and low frequent offsets of the SOV and keep the SOV at an earth-fixed Required Position. Three PID stiffness settings were programmed, representing soft (PID1), medium (PID2) and stiff (PID3) stiffness and damping settings.
PSDs and RAOs of the motions of the buoy under the influence of various PD settings by the SIL system are presented in Figure 35. PSDs and RAOs of the mooring line and hawser loads are presented in Figure 36.
The results presented in these figures show that the DP system reduces the hawser loads and low frequent motions of the buoy significantly. This is summarised in the figure below. Furthermore also the wave frequent response is reduced significantly. Based on these observations it is recommend to use DP control of charging vessel iso backward pull.

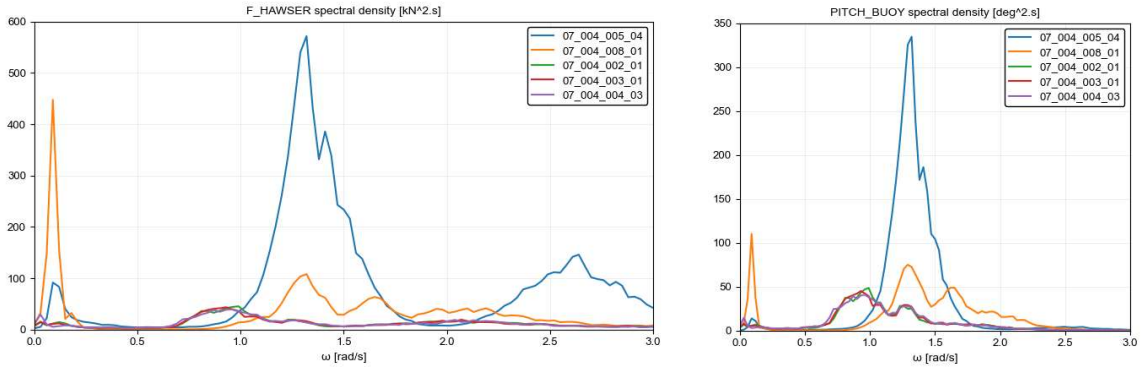


Figure 7-1: PSD of hawser loads (left) and pitch (right) for Setup C2 (orange); Setup C3 (1 t BP: blue; PID1: green; PID2: red; PID3: purple)

7.5.6 MultiCat

PSDs and RAOs for the motions of the buoy with the SOV or the MultiCat attached in Operational (H_S = 1.0 m) and 1yr storm (H_S = 2.9 m) waves are presented in Figure 37. PSDs and RAOs of the mooring line and hawser loads are presented Figure 38. These results show:

- The motions of the buoy and loads in the hawser are similar for cases where the MultiCat is connected as where the 44 m SOV is connected.
- The 1yr storm sea state shows more low frequent response than the operational sea state. The wave frequent response in the 1yr storm condition is less; a shift of the response spectra to lower frequencies can be observed.

7.6 Response Buoy B

The motion RAOs of Buoy B alone (Setup B1) and with the SOV present, but no hawser attached (Setup B3) are presented in Figure 39 (Top). The RAOs presented in this figure show in general a good agreement.
Motion RAOs of Buoy B with the SOV and various configurations of the hawser attached (Setup B2) are presented in Figure 39 (Bottom). The results in this figure show the attachment and configuration of the hawser has large influence on the pitch and yaw. This can also be observed in the RAO of the hawser loads as shown in Figure 40.

7.7 Hawser loads

7.7.1 Buoy C

Figure 41 shows the peaks and troughs in the hawser loads with 0 t, 1 t and 2 t BP by the SOV in the H_S = 1.0 m, T_P = 5.0 s wave condition. The distribution function of the troughs shows that for 0 t and 1 t BP about 30% of the troughs reduce to 0 kN, while with 2 t BP the number of slack line events reduces to about 3%.The distribution function of the peaks shows maximum loads up to 67 kN with 2 t BP and 54 kN for 1 t BP.

7.7.2 Buoy B

Figure 42 shows the peaks and troughs in the hawser loads for various hawser configurations tested in Setup B2. The results presented in this figure show the following:

- The largest loads (04_70_002_01; green) are observed in the highest wave conditions (H_S = 4.0 m, T_P = 9.2 s). The maximum loads are approx. 1500 kN. Elongation of the hawser length from 40m to 65m (04_070_003_01; orange) reduces the maximum loads to approx. 800 kN.
- Comparison of Hawser B and B Alternative shows similar distribution functions of the maximum loads and somewhat smaller troughs for B Alternative.

8 CONCLUSIONS AND RECOMMENDATIONS

Based on the results presented in this report, the following conclusions and recommendations seem justified:

- In Buoy only tests (Setups B1 and C1) the buoys are free to weathervane. In general the buoys weathervane such that the appurtenances are at the leeward side of the buoys. In some cases buoys show large yawing motions. Some rotations occur rapidly due to extreme wave events and asymmetry first order yaw loading. Other rotations are slow due to asymmetric wave drift loading.

- During extreme event the following typical behaviour occurs:
  - A steep breaking wave overtops the buoy completely and gives it a rapid horizontal setback. This results in peak loads of the wave ward mooring line. For Buoy C water enters the deckhouse through the hose opening.
  - When the wave has passed the buoy restores and overshoots in wave ward direction. This results in slack of wave ward mooring line and a peak load of leeward mooring line. The skirt and underside of the buoy come out the water, slamming occurs.

  Water overtopping the buoys, high mooring line loads in the wave ward lines, slack mooring lines and slamming on the skirt occur during extreme wave events. It is recommended to take the risk and effect of water overtopping the buoy and of slamming loads on the skirt into account in the design of the buoys.

- For the tested sea states up to H_S = 2.9 m the response transfer functions of Buoy C without the hawser attached (Setup C1) are mostly linear. With the hawser attached (Setups C2 and C3) the modes of motion in-line with the waves and SOV (surge and pitch) are affected by the hawser loads. The motions of the buoy, especially pitch, follow the response of the SOV and hawser, mainly increasing the low frequent motions of the buoy.
  The response of the hawser loads increases when Backward Pull is applied by the bunkering vessel (Setup C2: 1 t, 2 t).
  With 1 t Backward Pull is applied by the SIL model (Setup C3), the low frequent hawser loads are less than when the 1 t Backward Pull is applied by a wire at the stern of the SOV. This indicates the low frequent phenomena are underestimated by the SIL approach; while the wave frequent hawser loads are overestimated.
  With a DP system applied through the SIL model the hawser loads and low frequent motions of the buoy reduce significantly. It is therefore recommend to use DP control of charging vessel iso backward pull.
  The motions of the buoy and loads in the hawser are similar for cases where the MultiCat is connected (by means of the SIL model) as where the 44 m SOV is connected.

- The motion RAOs of the SOV are not influenced by the hawser. They are influenced by transverse standing waves in the basin, due to reflections from the vessel and buoy, once compared to undisturbed RAOs from diffraction analysis.

Wageningen, September 2025
MARITIME RESEARCH INSTITUTE NETHERLANDS

F. Jaouën, MSc.
Manager Offshore

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[6] DNVGL-ST-0111, 2018

PROVIDED INFORMATION

Item	Date	Content	Reference
1	18-03-2022	Buoy B Mooring system	e-mail: *2-6431-0 3 5 m Demo buoy and mooring system*
2	18-03-2022	Buoy C Mooring system	e-mail: *2-6431-0 8 2 m buoy and mooring system*
3	18-03-2022	Buoy B geometry	*E-buoy top view - Preliminary - for Marin.pdf* *E-buoy side view - Preliminary - for Marin.pdf* *E-buoy 8.2 m size Marin PRELIMINARY rev 1.dwg*
4	18-03-2022	Buoy C geometry	*E-buoy (DEMO) top view - for Marin test rev C.pdf* *E-buoy (DEMO) side view - for Marin test rev C.pdf* *E-buoy (DEMO) section - for Marin test rev C.pdf* *Concept layout Buoy C - 3.5 m.DWG*
5	18-03-2022	Buoy B particulars	*E-Buoy 8.2 m concept - Weight and stability - Scaled 10mx0.8 rev 1.xls*
6	18-03-2022	Buoy C particulars	*Weight & stability 3.5 m buoy rev C.xlsx*
7	18-03-2022	Buoy B & C floating hose	*Properties floating cable in hose.xlsx*
8	22-06-2022	Buoy B particulars Buoy B mooring Buoy B hawser Buoy B hawser ALT Buoy B seabed cable Buoy C particulars Buoy C hawser	2-6431-1 / TN-BES-Disc-L-001 Rev. B
9	09-03-2022	Dutch OWF environmental conditions	*extremevalue_owf.xlsx*
10	16-03-2022	MultiCat properties	*DD0760_Capability_Report_Rev-01-BV.pdf*

BETTER SHIPS, BLUE OCEANS

Real-time simulation study for feasibility assessment of an E-tower charging station at the North Sea

Real-Time Simulations

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Real-time simulation study for feasibility assessment of an E-tower charging station at the North Sea

Real-Time Simulations

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SUMMARY

The WP5 real life marine operation demonstration aligns with the broader goals of the MAGPIE (sMArt Green Ports as Integrated Efficient multimodal hubs) project, which is co-funded by the European Union's Horizon 2020 program. MAGPIE aims to accelerate the decarbonization of port-related transport through smart, green, and digital innovations. The automated trucking and charging system is one of ten key demonstrations within MAGPIE, contributing to the project's mission to create scalable, interoperable solutions for future logistics.

The WP5 demo aimed at investigation and demonstration of the feasibility of offshore charging of electricity to vessels moored in waiting areas or near offshore wind farms, enabling them to switch off generators and operate with zero emissions while awaiting port entry or performing offshore tasks. The key points of the WP5 demo are:

- Investigation and demonstration of the feasibility to supply renewable electricity to vessels moored in waiting areas or near offshore wind farms, so vessels can shut down auxiliary engines and eliminate local emissions.
- Prove safe, reliable high-voltage transfer using offshore grid connection, dynamic mooring, and HV plug systems.
- Deliver operational, regulatory, and business-case data for uptake by other European ports within the Green Ports Master Plan.

Through the MAGPIE project, EU aims to take action to accelerate the introduction of green energies and logistic optimisation through automation and autonomous operations in ports. Under the work package 5 (WP5) of the project, Bluewater (a consortium partner) designed an offshore e-charging solution involving a fixed tower in the North Sea. The proposed operation involves an electrically propelled Service Operations Vessel (e-SOV) arriving to an e-Tower (similar to a tower loading unit), located nearby a wind farm in the North Sea, pick-up the messenger lines and connect the hawser. This is a manned operation and thus motions at the bow of the vessel largely determine the safe operability limits. Considering the prolonged charging period, crew comfort at the bridge is also of interest.

As a partner in the MAGPIE project, MARIN together with Bluewater and Van Oord (other consortium partners), performed a 3-day simulation campaign at its Seven Oceans Simulation centre to assess feasibility of the operation and investigate safe operability limits. During the simulations, the e-SOV bridge was set up at the Large Motion Simulator (LMS) of MARIN, with an active motion base. For simulating deck operations, a VR setup was deployed in the mixed reality Lab, placing the deckhand virtually on the bow of the e-SOV. In some simulations, the vessel was also operated from a multi-purpose bridge simulator without a motion base, while deck operations were simulated on the LMS with an active motion base.

During the simulations, the captain focused on manoeuvring the vessel into position, while the deckhand provided guidance from the deck (heli or mooring deck) to ensure accurate alignment for messenger line reception. The deckhand was visible to the captain as an avatar on the fore deck. Once near the e-Tower, continuous communication was maintained between bridge and the deck. The deckhand walked through all operational steps, including confirming hawser and electrical line connections. These actions were animated in the simulation, showing the steady lowering and winching of lines, following the expected duration. While physical tasks like grabbing the messenger lines were not performed, all procedural steps were followed to ensure compliance.

During the 3-day simulation campaign, 19 simulations were performed with varying weather conditions. Among them, 12 were arrival runs, 4 departure runs, and 3 emergency runs with departure scenarios. Evaluations were performed both in terms of vessel manoeuvring capabilities, and human safety and comfort for involved bridge and deck operation.

The results suggest that for the simulated conditions, the studied e-SOV proved to have sufficient power to perform arrival, residence, and departure maneuvers safely. Even with a partial failure (50% power loss, one stern and one bow thruster), the vessel managed to safely depart in the specified environment. Considering only the maneuvering aspect, almost all runs were commented as safe by the simulator instructor and the captain. However, with increasing severity of weather, the maneuvers got more challenging. It was also observed that at high seas with large swell, for the specified hawser, maintaining hawser load proved to be challenging with some back thrust.

With a length of roughly 84m, the vessel had a relatively large motion in severe weather, which caused discomfort during deck operation. In such harsh weathers, it is preferrable to move the manned operation to the mooring deck for better safety. Nevertheless, considering the NORDFORSK criteria, vessel motion remained below limit in all studied conditions. From the human factor side, the captains did not mention discomfort at the bridge due to large motions. However, the deck personnel expressed discomfort with equivalent sea height of 2.5m.

Overall, following the simulations, the concept has been proven valid. The available power on the vessel proved enough to perform the arrival and departure manoeuvres safely, up to moderate North Sea environment (12.5 m/s wind and 2.5 m total sea height). In case of more extreme conditions (20 m/s wind and 3.0 m total sea height), the vessel remained controllable with some challenges. Prolonged manned operation on open deck at such sea states are not recommended.

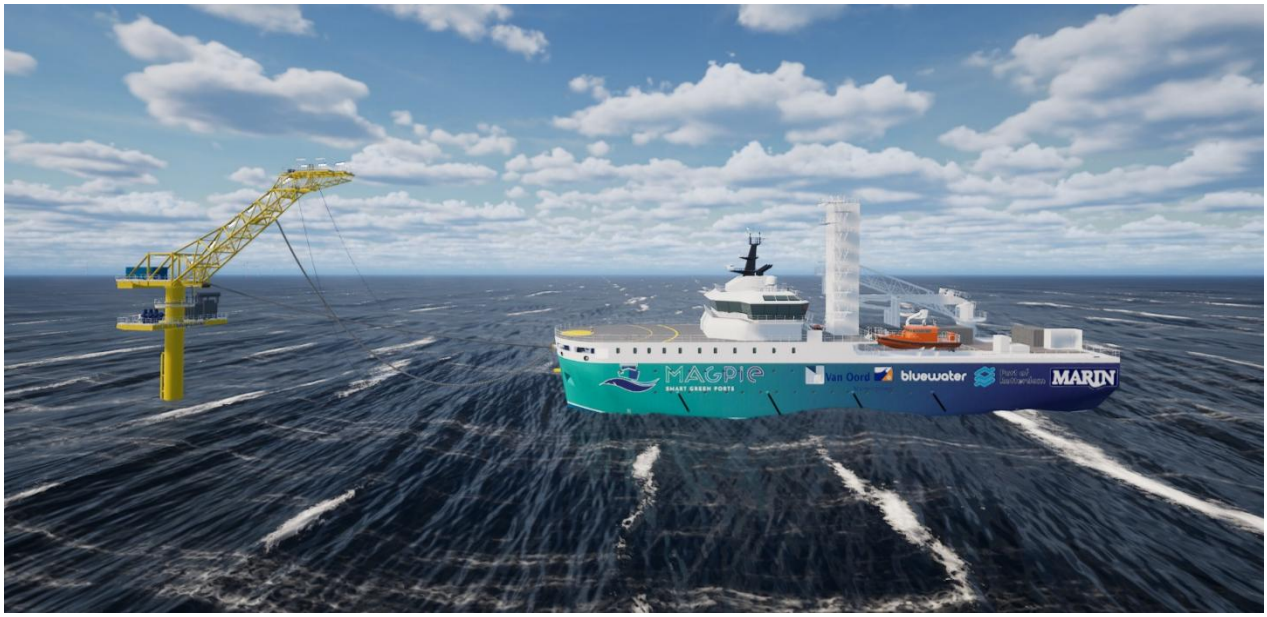


Figure 1: Visual representation of the operation.

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1 INTRODUCTION

1.1 Background

The EU MAGPIE project aims to take action to accelerate the introduction of green energies and logistic optimisation through automation and autonomous operations in ports. A living lab approach is applied in which 12 technologies are developed or demonstrated and non-technological innovations are developed. The combined results feed into the masterplan for the European green port of the future, aiming at full decarbonisation by 2050. Organization and Work Packages (WP) under the project are shown in Figure 1-1.

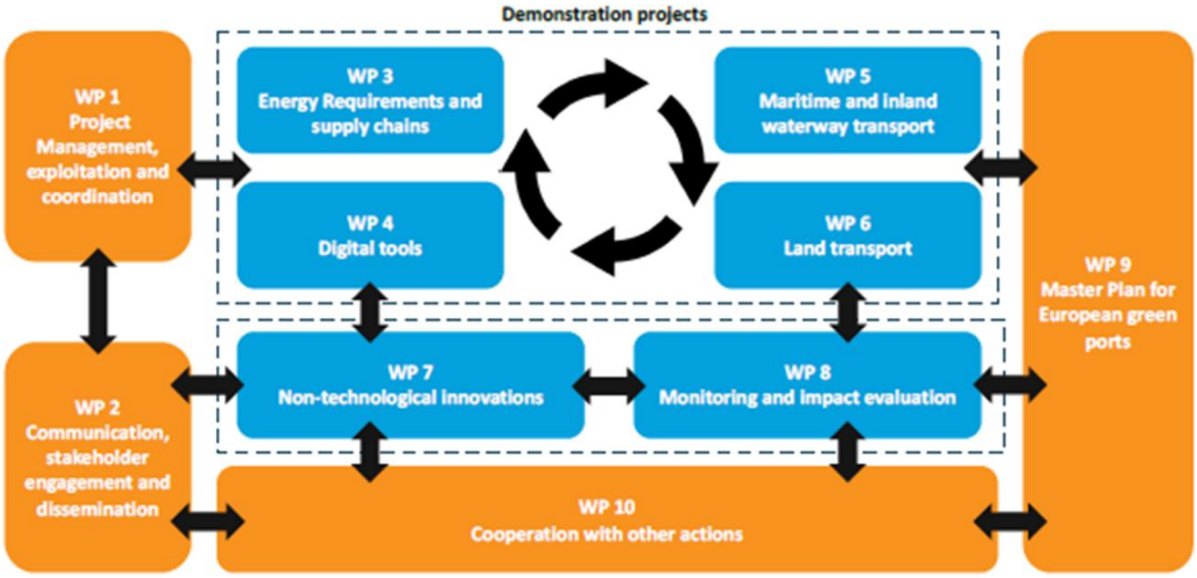


Figure 1-1: Organization of EU MAGPIE project

Under work package 5 (WP5) of the project, the participant, Bluewater, is expected to design and demonstrate an offshore e-charging solution in the range of 1-20+MW. As part of the task, two designs of offshore e-charging buoys were tested at the Shallow Water Basin at MARIN in 2022, followed by Computational Fluid Dynamics (CFD) simulations. The basin tests showed that extreme wave events can lead to severe wave overtopping of the buoy, high mooring line loads and slamming on the skirt. This important observation confirmed the challenges of permanently mooring a relatively small size buoys in severe North Sea wave conditions.

Based on the techno-economic evaluation of the e-charging buoy concept, Bluewater's search for alternative concepts resulted in a shift towards a solution with a fixed tower and an aerial electrical cable. The fixed tower solution seemed more suitable for desired areas for e-charging, in particular, areas in the vicinity of bottom fixed wind parks in the North Sea.

The proposed operation involves an electrically propelled Service Operations Vessel (e-SOV) arriving to an e-Tower (similar to a tower loading unit), located nearby a wind farm in the North Sea, pick-up the messenger lines and connect the hawser (mooring) and charging cable, and charge the batteries. Part of the operation requires personnel on deck and thus motions at the bow of the vessel largely determine the safe operability limits. Representative visuals for the study are shown in Figure 1-2.

The messenger lines may be picked up either from the helideck/forecastle deck or the mooring deck of the vessel. First, the hawser line is fed to the chain stopper in the mooring deck. Following the hawser connection, once the vessel is stable, the power cable is expected to be winched in and will be fed into the charging unit located at the mooring deck of the vessel. It is expected that the vessel will be able to

weathervane during the charging period, by using the hawser line. Although similar to anchoring condition, considering the relatively small size of the vessel, crew comfort at the bridge during the charging time is also of interest.
Once charged or when required by circumstances, the vessel would be able to use a quick release mechanism for releasing both the charging cable and the hawser line, and depart safely from the location.

To demonstrate the concept in operation and to assist with possible design iterations, the consortium approached the Maritime Operations department of MARIN to perform a nautical study into the feasibility of the e-charging operations. To assess the feasibility of the operation together with operability limits, real-time simulations have been performed in which arrival, residence, and departure scenarios under various conditions have been tested. The test conditions were determined based on the prevailing environment in the studied area and in concert with the client. Besides the general operations, the simulations also included some emergency scenarios like loss of propulsion of the e-SOV.

This report describes the outcomes of the real-time simulation study performed during a 3-day simulation campaign held at the Seven Oceans Simulator Centre at MARIN, Wageningen.

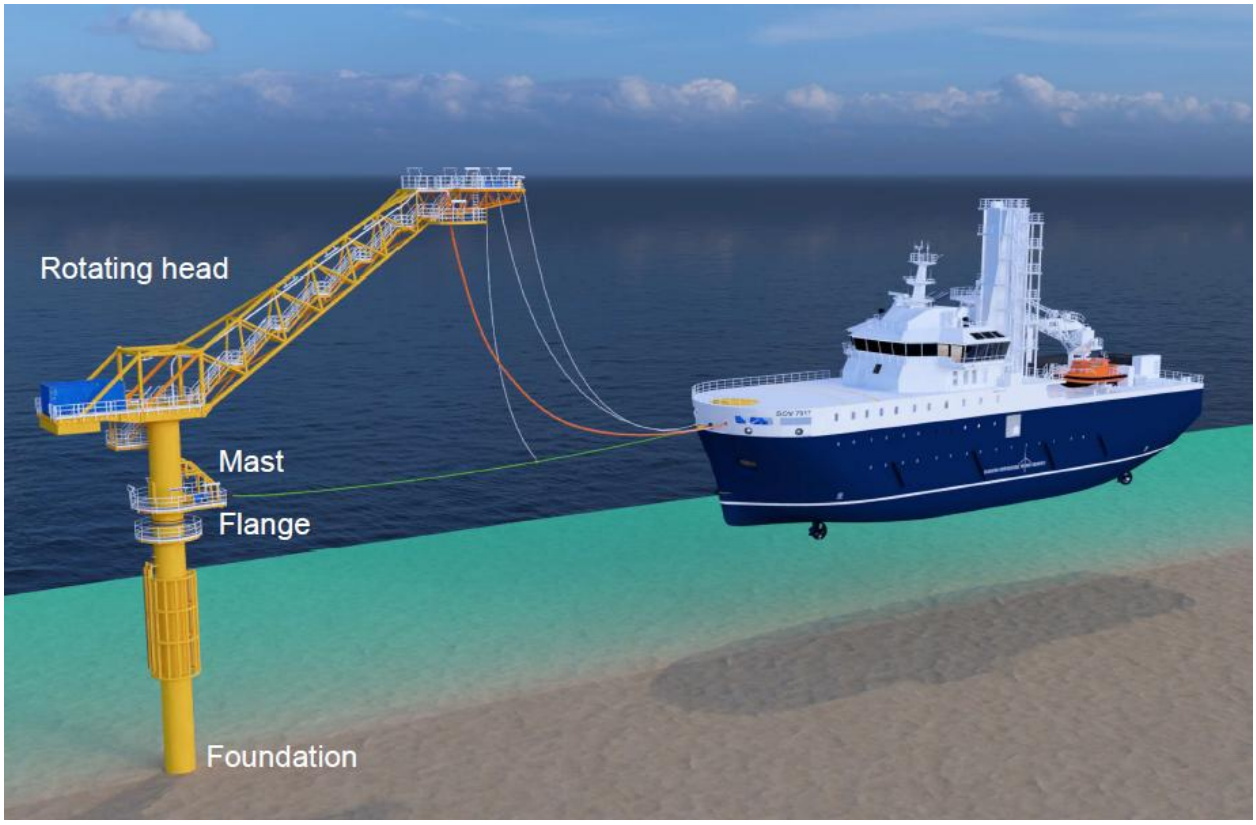


Figure 1-2: Visual representation of e-SOV connected to an E-Tower for charging (source: Bluewater).

1.2 Objectives and approach

The objectives of the real-time simulations were to demonstrate the operation in a simulation environment and to evaluate the environmental limits for conducting arrival, residence, and departure manoeuvres of an e-SOV on a Single Point Mooring (e-Tower). The operability limits are largely governed by the manned operation needed on the bow of the e-SOV for establishing the hawser and the electrical connection, and the crew comfort at the bridge during the charging process. Thus, the study aimed at defining operational boundaries based on safe human operation during arrival and departure procedures.

To reach the objectives, real-time manoeuvring simulations have been carried out at the Large Motion Simulator (with an active motion base), coupled with a Virtual Reality (VR) setup, to simulate arrival, residence, and departure scenarios. Simulations were carried out under various environmental conditions, considering calm, moderate, and extreme conditions in that area. The simulations were executed between 17th-19th March 2026. Each run has been analysed by a nautical expert. An assessment of the safety, workability, and manoeuvring reserves has been made based on the simulation logs. However, making quantitative assessment of the complexity of the involved manned operation is not within the scope of the real-time simulation study.

It is expected that the demonstration will provide an important step toward an industry accepted solution that is safe, reliable, and compliant with the relevant offshore industry standards.

1.3 Structure of this document

This document describes the results of the feasibility study and is divided in the following sections:

- Database description;
- Execution of the simulations;
- Presentation and discussion of the results;
- Conclusions and recommendations.

2 DATABASE DESCRIPTION

2.1 General

The simulator database contains the following main elements:

- Geographical area;
- Object description (e-SOV and e-Tower);
- Environmental conditions;
- Simulation scenarios.

These elements are described in the following sections.

2.2 Geographical area

For the study, the intension was to select a representative location covering possible sites along the Dutch coast. Following discussions, the Borssele 4 Blauwwind farm in the North Sea was selected. The e-Tower was placed within the 500m safety zone of the wind farm, with a rough distance of 250m from the closest wind turbine. An Electronic Nautical Chart (ENC) of the area was used as basis for modelling the area, with a constant water depth of 30m. Figure 2-1 shows the ENC of the area, together with global location of the wind farm. Wind turbines in the vicinity of the e-Tower were included in the area.

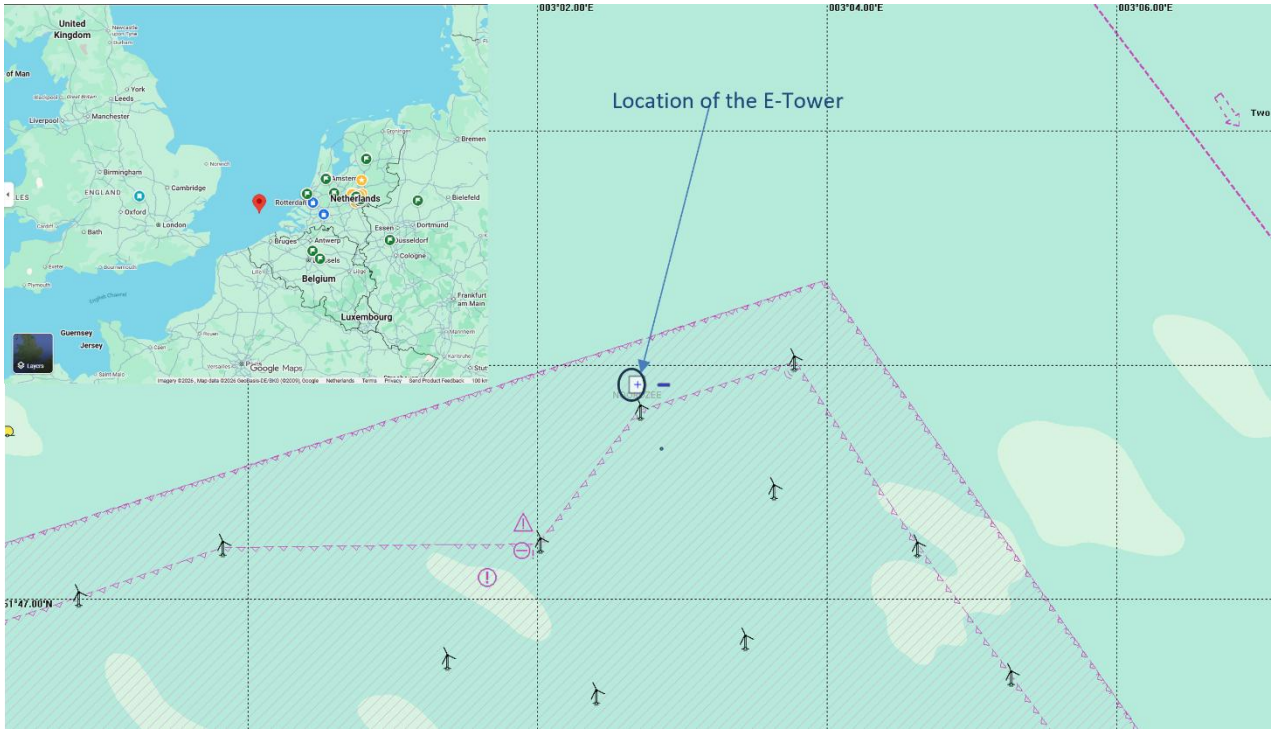


Figure 2-1: Project area and location of the e-Tower.

2.3 Electrically Propelled Service Operations Vessel (e-SOV)

For the simulations, the Service Operations Vessel was modelled as a free-sailing model with manoeuvring capability. The vessel was equipped with two Azimuthing stern thrusters and two Azimuthing in-line bow thrusters. The captain had access to control all four thrusters from the bridge of the vessel. The main dimensions of the vessel are 84.0x18.90x5.0 m. General assembly and representative visuals of the vessel are shown in Figure 2-2 and Figure 2-3. The numerical model of the vessel is based on a service vessel (Figure 2-2) model previously used for a basin study at MARIN. However, for visual representation (Figure 2-2), a different service vessel model has been used with proper scaling.

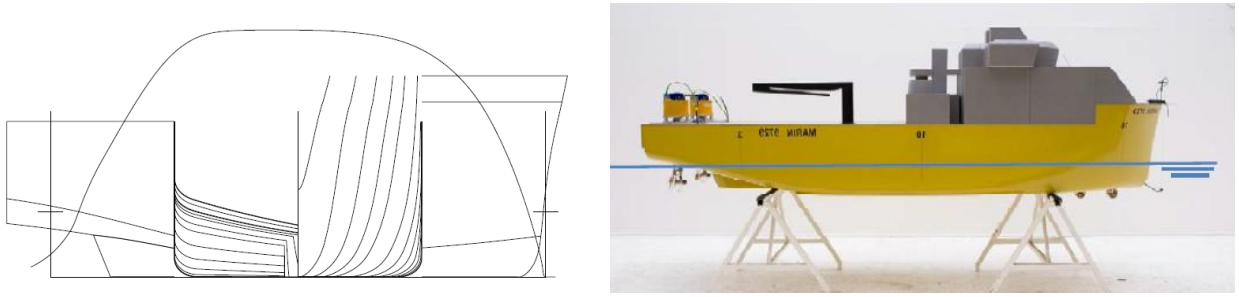


Figure 2-2: Hull lines of the service vessel used for the simulation study (left), together with a picture of the model used in MARIN's basin study.



Figure 2-3: Impressions of the representative e-SOV from real-time simulations.

Main particulars of the vessel are shown in Table 2-1, together with propulsion powers and limits in Table 2-2.

The manoeuvring model has been derived from a service vessel of similar size by scaling the manoeuvring coefficients. The mathematical manoeuvring model consists of a large number of parameters describing amongst others:

- The manoeuvring behaviour of the ship (hydrodynamic properties of the hull in the water);
- First and second order response to waves;
- Wind forces;
- Characteristics of the propulsion system;
- Bollards and winches to allow connecting the hawser.

Table 2-1: Main particulars of the e-SOV.

Designation	Symbol	Unit	Magnitude
Length between perpendiculars	L_{pp}	[m]	84.0
Breadth	B	[m]	18.9
Draft fore	T_F	[m]	5.00
Draft aft	T_A	[m]	5.00
Trim		[deg]	0.00
Displacement	Δ	[tonnes]	6244.7
Waterline area	A_{wl}	[m^2]	1483.1

Table 2-2: Propulsion characteristics of the e-SOV.

ID	Type	Diameter of propeller [m]	Position of propeller centre			P_shaft [kW]	Effective Pull Transit [kN]	Nominal Thrust [kN]	Speed up time [s]	Azimuth Velocity [deg/s]
			X from st10 [m]	Y from CL [m]	Z from Keel [m]					
1	Azimuthing thruster	2.7	-42	4.725	1.5	1980	356.8	400	20	8.0
2	Azimuthing thruster	2.7	-42	-4.725	1.5	1980	356.8	400	20	8.0
3	Azimuthing thruster	1.7	35.7	0	-1	900	-	150	20	8.0
4	Azimuthing thruster	1.7	29.4	0	-1	900	-	150	20	8.0
Total (for transit)						4000	713.7			

To model the ship response in waves, dedicated diffraction analysis was performed (frequency domain) to calculate the wave forces acting on the vessel. The Pilot Card of the vessel is included in APPENDIX 1.

2.4 E-Tower, Hawser and Power Cable

A 3-dimensional model of the e-Tower was included in the database, following the drawing provided by Bluewater. The e-SOV gets connected to the e-Tower by a 40m or 60m long hawser line (both lengths were tested). Following the hawser connection, the power cable gets connected. Once connected, the e-SOV is allowed to weathervane around the e-Tower under influence of the environment. The e-Tower could also be pre-aligned, with a rotational speed of 360deg/min.

Numerically, the tower was modelled as a body with provided dimensions (by Bluewater), and a mass of 511000 Kg. The cog was stated to be at 3m above the water line. The tower had free yaw rotation damped by linear and quadratic damping with values.

The hawser and power cable characteristics are provided in Table 2-3, together with elongation curve for the hawser in Table 2-4, as supplied by Bluewater. Layout and visual representation of the e-Tower is also shown in Figure 2-4. For the winches lowering the lines, a lowering speed of 0.5m/s was used.

Table 2-3: Mooring Hawser and Electrical Calbe Characteristics.

	Hawser 1	Hawser 2	Power Cable	Messengers
Material	Nylon	Nylon	PU elements (Igus E-loop) with core of UHMWPE (Duraten Pro P)	Polypropylene (High visibility)
Length [m]*	40	60	45-50 65 for Hawser 2	35
MBL [kN]	3030	3030	220	103
Elongation at break [%]	19	19	3.5	
Diameter [mm]	112	112	300	24
Dry mass/meter [kg/m]	7.79	7.79	28.5 (incl. cables)	
Minimum bend radius (bend restrictor) [mm]	-	-	500	

Table 2-4: Elongation curve for the hawser line, provided by Bluewater.

Elongation [%]	Tension [kN]
0	0
2	72.792
4	166.815
6	288.135
8	454.95
10	758.25
12	1364.85
14	2183.76
16	2638.71
18	2881.35
19	3033

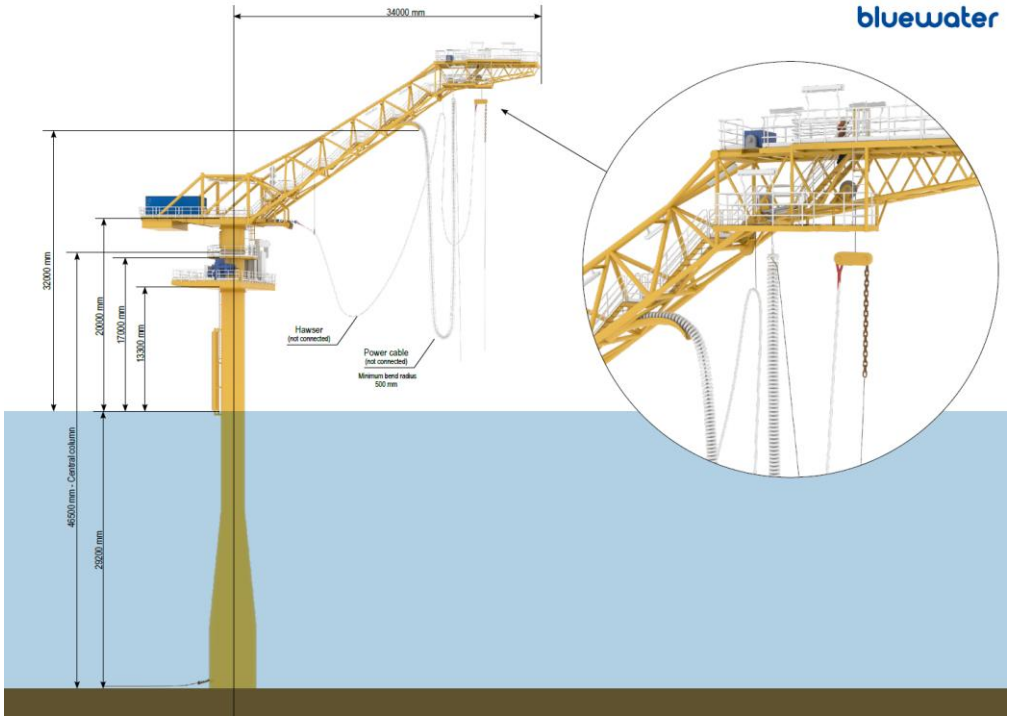


Figure 2-4: Dimensions and configuration of the e-tower, provided by Bluewater.

2.5 Metocean conditions

Due to absence of location specific environmental data, representative data was taken from a location roughly 215km north-east of the proposed study site (Blauwwind). The current data was selected based on the study location.

The wind directions are mainly between SSW (202.5º) to W (270º), with a predominant direction SW (225º). A uniform vector field is used to model the wind. Wind velocities mentioned in this document are the reference value at 10 m height level. The wind speed displayed on the simulator bridge are generally higher as a correction is applied for the difference in height between the 10m-reference level and the position of the wind sensor on the ship based on a standard vertical wind profile. Wind gusting is a standard effect in the simulator, the gusting is modelled with a Davenport spectrum.

Two separate wave fields were specified to represent sea and swell. Wind sea dominant direction is from SSW and dominant swell directions are from NNW (337.5º) and SSW (202.5º). Waves were also defined as uniform over the entire area. The actual parameters of the two wave fields (significant wave

height, peak period, main direction, peak enhancement factor) were set when starting up the run. In the simulations, a JONSWAP spectrum is assumed, which is distributed over a number of separate frequencies and directions.

Figure 2-5 shows the wind, sea and swell rose [Ref 1.]. The annual directional wind speed distribution and total sea distributions for representative location is shown in Table 2-5 and Table 2-6 [Ref 1.].

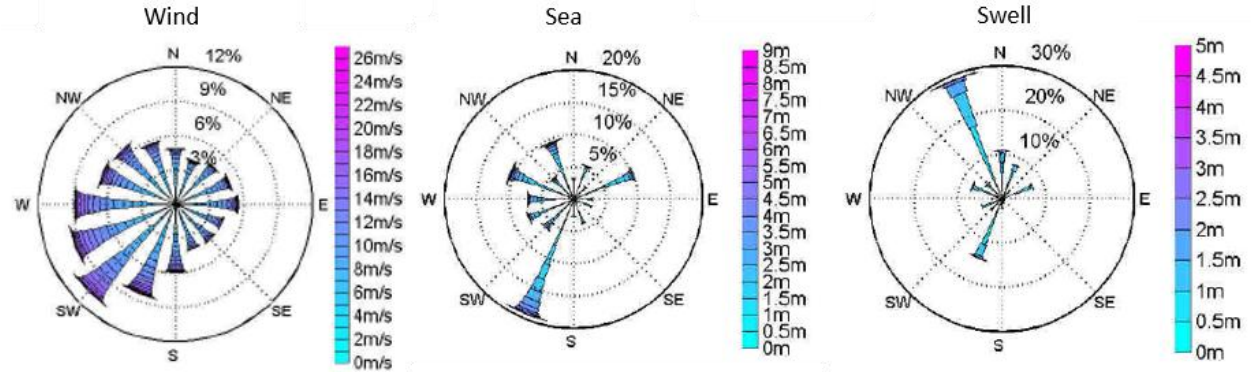


Figure 2-5: Wind, sea and swell rose

Table 2-5: Annual directional wind speed distribution at the location of platform L7B. [Ref 1.]

Speed\Dir	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	Total
0.00 - 1.00	0.06	0.05	0.03	0.06	0.05	0.06	0.04	0.07	0.05	0.05	0.05	0.05	0.06	0.05	0.03	0.05	0.84
1.00 - 2.00	0.15	0.15	0.12	0.13	0.14	0.13	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14	2.31
2.00 - 3.00	0.23	0.23	0.23	0.22	0.24	0.21	0.26	0.22	0.25	0.24	0.27	0.28	0.26	0.25	0.27	0.27	3.93
3.00 - 4.00	0.38	0.37	0.37	0.32	0.37	0.33	0.35	0.35	0.4	0.45	0.47	0.43	0.45	0.39	0.4	0.38	6.22
4.00 - 5.00	0.5	0.46	0.51	0.46	0.46	0.43	0.42	0.48	0.54	0.58	0.68	0.59	0.58	0.52	0.51	0.48	8.19
5.00 - 6.00	0.54	0.52	0.59	0.52	0.57	0.43	0.48	0.47	0.62	0.7	0.79	0.73	0.67	0.55	0.56	0.52	9.25
6.00 - 7.00	0.59	0.56	0.58	0.58	0.61	0.46	0.5	0.45	0.63	0.77	0.92	0.77	0.75	0.66	0.64	0.55	10.03
7.00 - 8.00	0.6	0.51	0.56	0.6	0.64	0.48	0.44	0.39	0.57	0.8	1	0.89	0.8	0.69	0.63	0.6	10.18
8.00 - 9.00	0.52	0.41	0.49	0.5	0.54	0.42	0.39	0.34	0.49	0.74	0.99	0.82	0.83	0.71	0.68	0.58	9.45
9.00 - 10.00	0.4	0.32	0.38	0.48	0.48	0.37	0.36	0.32	0.47	0.75	0.93	0.85	0.81	0.63	0.65	0.53	8.71
10.00 - 11.00	0.32	0.21	0.29	0.36	0.39	0.29	0.27	0.26	0.39	0.62	0.85	0.76	0.68	0.53	0.55	0.47	7.24
11.00 - 12.00	0.23	0.12	0.19	0.3	0.29	0.22	0.22	0.2	0.32	0.53	0.79	0.71	0.62	0.45	0.44	0.34	5.97
12.00 - 13.00	0.15	0.07	0.13	0.2	0.23	0.2	0.16	0.16	0.28	0.45	0.72	0.6	0.53	0.36	0.35	0.26	4.84
13.00 - 14.00	0.1	0.06	0.07	0.14	0.17	0.15	0.12	0.11	0.23	0.37	0.56	0.5	0.45	0.28	0.27	0.19	3.77
14.00 - 15.00	0.05	0.03	0.05	0.08	0.12	0.09	0.07	0.09	0.19	0.32	0.48	0.43	0.34	0.21	0.19	0.14	2.88
15.00 - 16.00	0.04	0.03	0.04	0.06	0.08	0.05	0.05	0.05	0.14	0.27	0.36	0.32	0.27	0.18	0.16	0.08	2.17
16.00 - 17.00	0.02	0.01	0.02	0.04	0.07	0.03	0.02	0.04	0.1	0.23	0.29	0.25	0.23	0.12	0.09	0.05	1.6
17.00 - 18.00	0.01	0	0	0.02	0.04	0.02	0.01	0.02	0.06	0.15	0.18	0.17	0.15	0.09	0.05	0.04	1.01
18.00 - 19.00	0.01	0	0	0.01	0.02	0.01	0	0.01	0.05	0.1	0.13	0.09	0.11	0.05	0.05	0.01	0.67
19.00 - 20.00	0	0	0	0.01	0	0	0	0	0.02	0.07	0.06	0.05	0.07	0.04	0.02	0.01	0.36
20.00 - 21.00	0	0	0	0	0	0	0.02	0.03	0.03	0.03	0.05	0.02	0.01	0	0.2		
21.00 - 22.00	0	0	0	0	0.01	0.02	0.02	0.01	0.02	0.01	0.01	0	0.1				
22.00 - 23.00	0	0.01	0.01	0.01	0.01	0	0	0	0.05								
23.00 - 24.00	0	0	0	0	0.01	0	0	0	0.02								
24.00 - 25.00	0	0	0	0	0	0	0.01										
25.00 - 26.00	0	0	0	0	0	0											
26.00 - 27.00	0	0															
Total	**4.89**	**4.13**	**4.67**	**5.1**	**5.48**	**4.38**	**4.3**	**4.17**	**5.97**	**8.43**	**10.74**	**9.5**	**8.89**	**6.95**	**6.7**	**5.69**	**100**

Table 2-6: Annual directional total sea (Hs) distribution at the location of platform L7B. [Ref 1.]

Hs\Dir	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5	Total
0.00 - 0.50	1.61	0.84	0.13	1.72	0.1	0.06	0.02	0.06	0.09	1.8	0.54	0.2	0.09	0.43	0.37	1.95	10.02
0.50 - 1.00	3.41	2.19	0.39	3.41	0.34	0.25	0.09	0.27	0.25	5.14	1.18	0.52	0.31	1.05	1.05	6.97	26.8
1.00 - 1.50	1.97	1.49	0.38	2.63	0.28	0.22	0.07	0.34	0.26	4.7	1.02	0.57	0.56	1.34	0.84	6.49	23.17
1.50 - 2.00	0.88	0.72	0.26	1.55	0.16	0.15	0.04	0.28	0.21	3.4	0.65	0.58	0.8	1.17	0.53	3.75	15.14
2.00 - 2.50	0.35	0.33	0.14	0.86	0.09	0.08	0.01	0.13	0.13	2.3	0.49	0.5	0.74	0.88	0.36	2.1	9.5
2.50 - 3.00	0.13	0.19	0.08	0.44	0.05	0.03	0.01	0.05	0.06	1.61	0.38	0.3	0.58	0.72	0.26	1.2	6.08
3.00 - 3.50	0.04	0.09	0.07	0.21	0.02	0.01		0.01	0.03	1.13	0.3	0.16	0.4	0.5	0.17	0.75	3.87
3.50 - 4.00	0.03	0.06	0.02	0.13	0.01	0		0	0.01	0.7	0.21	0.09	0.25	0.4	0.13	0.45	2.49
4.00 - 4.50	0.02	0.02	0.01	0.05	0	0				0.39	0.15	0.04	0.14	0.26	0.09	0.28	1.45
4.50 - 5.00	0.01	0.01	0.01	0.01	0					0.19	0.07	0.01	0.07	0.18	0.06	0.16	0.77
5.00 - 5.50	0	0.01	0							0.08	0.05	0	0.03	0.09	0.03	0.09	0.38
5.50 - 6.00	0	0	0							0.02	0.02	0	0.01	0.05	0.02	0.05	0.18
6.00 - 6.50		0								0.02	0.01	0	0.01	0.02	0.01	0.03	0.09
6.50 - 7.00										0	0		0.01	0.01	0	0.03	0.05
7.00 - 7.50													0	0	0	0.01	0.01
7.50 - 8.00													0	0	0	0	0.01
8.00 - 8.50														0		0	0
8.50 - 9.00																	
9.00 - 9.50																	
Total	**8.46**	**5.95**	**1.49**	**11.02**	**1.05**	**0.81**	**0.24**	**1.16**	**1.04**	**21.47**	**5.07**	**2.97**	**3.99**	**7.09**	**3.91**	**24.29**	**100**

In the study area, the current is mostly tide driven. The two principal current directions are ENE (67.5º) (Figure 2-6) and WSW (247.5º), representing ebb and flood current, respectively. During the simulations the water level was kept constant.

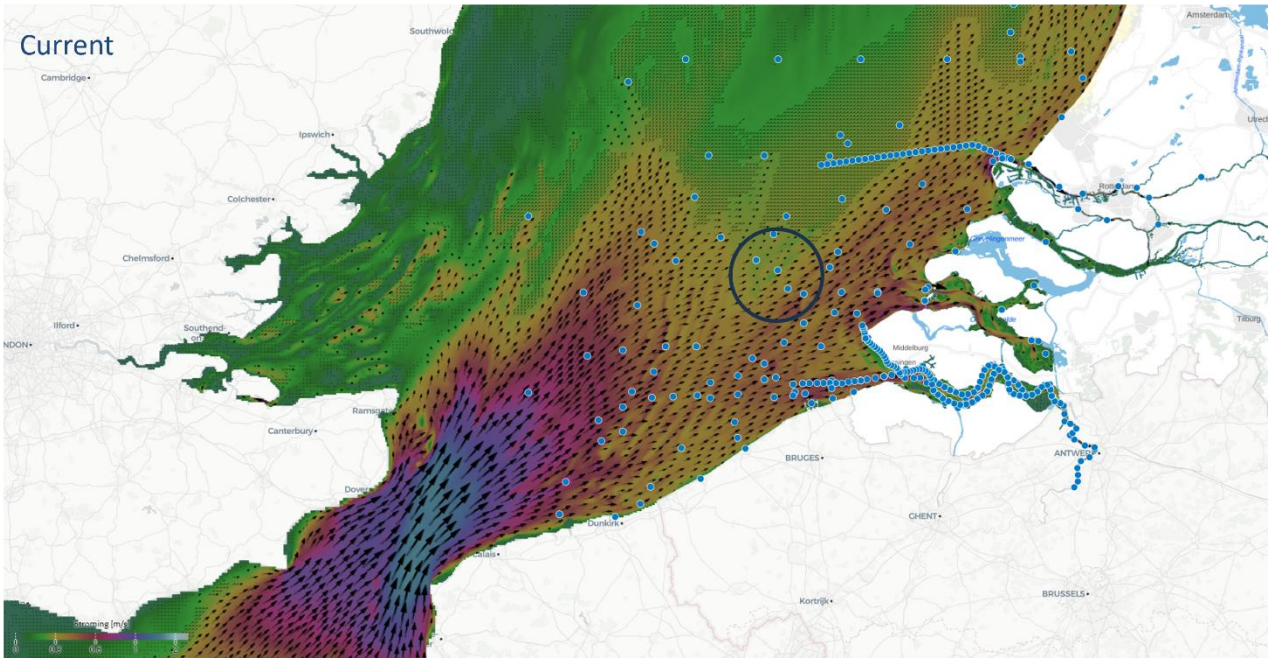


Figure 2-6: Current field in the study area.

2.6 Simulation scenarios

Scenarios define the area, the vessel, the metocean conditions and the initial state at the start of the run (vessel speed, rate of turn, etc.). For the simulations, a few basic scenarios were prepared for arrival and residence/departure manoeuvres. As the simulations involve only the vessel and tower, it was relatively easy to adapt these scenarios by moving the vessel to another starting location and adjust other relevant parameters such as the environmental conditions. In this way a number of other scenarios were created.

3 EXECUTION OF THE SIMULATIONS

Real-time manoeuvring simulations were carried out between the 17th and 19th of March 2026, at MARIN's Seven Oceans Simulator centre (SOSc). The involved simulators/ facilities were the Large Motion Simulator (LMS), the Multi-purpose Simulator (MPS), and the Maritime eXperience (MX) Lab. Participants and observers in the project were:

Participants	Position	Organization
Cornel Leijerzapf	Chief Officer 'Boreas'	Van Oord
Klaas Frik	Chief Officer Offshore Energy	Van Oord
Elon Hendriksen	Superintendent Offshore Energy	Van Oord
Harro Vaags	Sustainability Engineer	Van Oord
Evert Han Huernink	Tender Manager	Bluewater
Bastiaan van den Berg	Technology Manager	Bluewater
Moritz Palm	Sr Mooring & Subsea Engineer	Bluewater
Kees van Beveren	Marine Superintendent	Bluewater
MARIN Team		
Thom van der Hoff	Instructor	MARIN
Jaap de Wilde	Sr. Project Manager	MARIN
Rick Faber	Sr. Software Engineer	MARIN
Giorgio Ballestin	Sr. Specilist	MARIN
Heike Diepeveen	Project Manager	MARIN
Hafizul Islam	Project Manager	MARIN

Each day started at around 08:30 with a briefing and ended at around 16:30. On the first day, the study started with a general briefing, during which MARIN's project manager presented information about the simulator database and proposed programme.

The setup for runs were discussed and decided in a prior meeting with representatives from the Magpie consortium. During the campaign, the runs were updated, following suggestions from the clients and instructor. Briefings were held at intervals to discuss results of the runs. At the end of each simulation, a questionnaire was filled in by the captain performing the manoeuvre. The deck hands were also interviewed to record their experience and comfort level.

All simulations were performed by the two captains from Van Oord, Cornel Leijerzapf and Klaas Frik. Both captains have substantial offshore experience, with good familiarity with DP assisted vessels. Their exposure to hawser dependent mooring systems have been limited. The deck operations were performed by Elon Hendriksen and Harro Vaags, also from Van Oord. The participants altered among themselves for different runs, which provided a variation in experience and feedback.

A meeting room was available for the duration of the simulations for debriefing of the runs. A direct video link allowed observation of the runs from the debriefing room.



Figure 3-1: Debriefing room

On the last day of simulations, a demo was hosted with roughly 20 partners from the Magpie project to give them a preview of the expected operation at sea.

3.1 Simulator bridge setup

During most of the simulations, the vessel was controlled from the LMS (Figure 3-2), with the LMS motion base active. For these cases, the manned operation part was simulated (through VR) at the MX Lab (Figure 3-3). For roughly seven simulations, the vessel was controlled from the MPS (without motion base) (Figure 3-5), and the deck operation was simulated on the LMS with the motion base active (Figure 3-4).

The motion base in the LMS is designed to produce representative motions based on simulation outputs by using motion cueing. Due to physical/ hardware limitations, it is not possible to reproduce the same motions of large vessels as experience in open seas in a simulation centre. As such, motion cueing is used to generate similar experience by using a combination of axial and rotational acceleration. Together with visual cueing this provides a realistic experience of the motions on board a ship in waves.

All bridge simulators from MARIN are equipped with a standard console providing controls for telegraph, rudder(s) and thruster(s). Various displays show the conning, ARPA radar and electronic chart. The conning display (see Figure 3-6, left panel) shows the following information:

- RPM propeller(s);
- Rudder angle (analog/numeric);
- Course (heading and COG);
- Speed (Dual axis Doppler log);
- Rate of turn (analog/numeric);
- Wind direction (analog, absolute or relative);
- Wind speed;
- Under Keel Clearance (fore, mid, aft; analog/numeric).



Figure 3-2: The Large Motion Simulator including the motion base (left), controls and Displays at the LMS bridge (right).



Figure 3-3: VR setup in the MX Lab

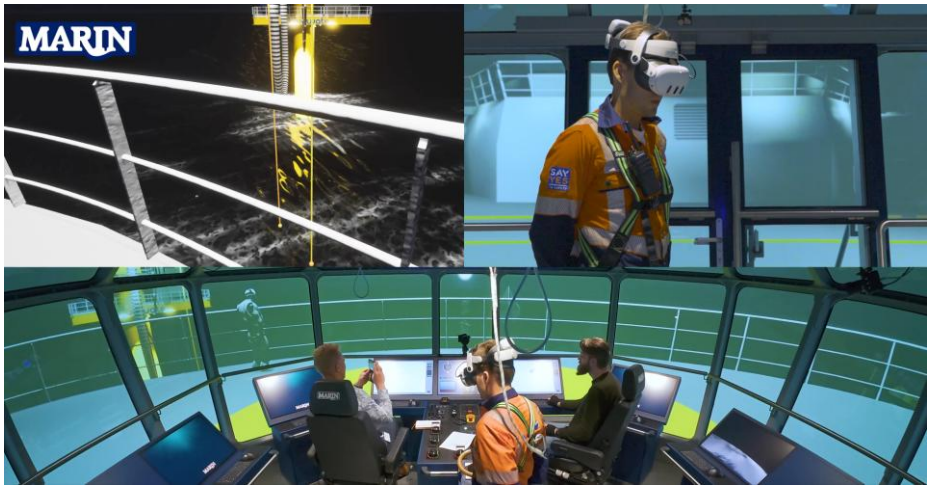


Figure 3-4: VR setup on the LMS



Figure 3-5: Bridge setup of the MPS



Figure 3-6: Displays simulator: conning (left; example, configuration depends on ship), ARPA radar (right)

The ECDIS is capable of showing the vessels position, course and speed over ground and the 'predicted path'.

3.2 Executed simulations

A total of 22 simulation runs were executed during the 3-day session. Table 3-1 gives a chronological overview of the runs that were carried out. Simulations were performed both in day and night time. Runs in blue (20, 21, 22) are simulations that were executed for demonstration to Magpie consortium members. These runs have been excluded from analysis.

Initial familiarization runs were set with mild environments (runs 1 and 2), which was gradually increased (runs 4, 5, 7, 8, 10, 11, 15, 16, 17, 18) to observe sensitivity in terms of vessel handling, and experienced and recorded motions at the vessel bridge and bow. Departure simulations were also performed in a similar manner, with gradual variations in environment (runs 3, 6, 12, 13). Some emergency scenarios were also simulated for departure (runs 9, 14, 19) to assess possible responses and propulsion capability. Both for arrival and departure runs, several simulation cases were repeated (with the same environmental conditions) with the motion bridge either representing motions of the vessel bridge or the vessel deck, to facilitate similar motion experience for both at the captain/s and deck hand/s.

Table 3-1: Run overview for Magpie study

Run	Date	manoeuvre	Time	Wind Speed	Wind Speed	Wind Dir	Hs Sea	Tp Sea	WaveDir Sea	Hs Swell	Tp Swell	WaveDir Swell	Current Speed	Current Dir	Run Description	Facility
				[m/s]	[knots]	[deg]	[m]	[s]	[deg]	[m]	[s]	[deg]	[m/s]	[deg]		
1	Day 1 (17.03.2026)	Arrival	Day	6.2	12.1	225	1.00	6.0	203	0.5	9.0	337	0.41	247	Familiarization run; mild conditions; with inactive motion base	LMS static + MX-Lab
2		Arrival	Day	6.2	12.1	202	1.50	7.0	202	1	12.0	337	0.41	67	Familiarization run with active motion base, increase in wind speed during simulation.	LMS dynamic + MX-Lab
3		Departure	Day	7.7	15.0	247	1.50	7.0	202	0.5	9.0	337	0.51	67	Departure in mild weather after reaching steady state; 40m hawser.	LMS dynamic + MX-Lab
4		Arrival	Night	7.7	15.0	225	1.50	7.0	202	0.5	9.0	337	0.41	67	Mild environment; 60m hawser	LMS dynamic + MX-Lab
5		Arrival	Night	12.9	25.1	247	2.00	8.0	247	1.5	13.0	337	0.41	247	Arrival in moderate conditions, 60m hawser | 85% annual weather	LMS dynamic + MX-Lab
6		Departure	Night	12.9	25.1	225	2.00	8.0	202	1.5	13.0	337	0.41	67	Departure in moderate condition after reaching steady state; 40m hawser.	LMS dynamic + MX-Lab
7	Day 2 (18.03.2026)	Arrival	Day	7.7	15.0	225	1.50	7.0	202	0.5	9.0	337	0.70	67	Mild environment with higher wind and waves; 40m hawser	LMS dynamic + MPS
8		Arrival	Night	12.9	25.1	247	2.00	8.0	247	1.5	13.0	337	0.50	200	Arrival in moderate conditions; 40m hawser | 85% annual weather	LMS dynamic + MPS
9		Departure	Night	14-15.4	27.2-29.9	225-340	2.80	9.0	202	1.3	13.0	337	0.60	247	Emergency departure while charging due to changed weather; wind shift	LMS dynamic + MPS
10		Arrival	Day	20.6	40.0	225	3.00	9.0	202	1.8	14.0	337	0.51	67	Arrival in severe weather | 94% annual weather	LMS dynamic + MPS
11		Arrival	Day	20.6	40.0	225	2.50	9.0	202	1.8	14.0	337	0.51	67	Arrival in severe weather | 94% annual weather	LMS dynamic + MPS
12		Departure	Day	20.6	40.0	225	2.50	9.0	202	1.8	14.0	337	0.51	247	Departure in severe weather | 94% annual weather	LMS dynamic + MPS
13		Departure	Night	15.4	29.9	202	2.80	8.0	202	1.5	13.0	337	0.31-0.60	247	Departure with increased sea and swell; 60m hawser	LMS dynamic + MX-Lab
14		Departure	Night	4.1	8.0	225	1.50	7.0	225	1	12.0	202	0.80	135	Emergency scenario with half-blackout | 1 bow & 1 stern thruster.	LMS dynamic + MX-Lab
15	Day 3 (19.03.2026)	Arrival	Night	7.7	15.0	290	1.50	7.0	290	0.5	9.0	337	0.60	67	Mild weater, messenger grabbing from below deck.	LMS dynamic + MPS
16		Arrival	Day	12.9	25.1	337	2.00	8.0	337	1.5	13.0	337	0.80	67	Moderate weather conditions, messenger grabbing from below deck.	LMS dynamic + MPS
17		Arrival	Night	20.6	40.0	225	3.00	9.0	202	1.8	14.0	337	0.80	247	Arrival in severe weather | 94% annual weather	LMS dynamic + MX-Lab
18		Arrival	Night	4.1	8.0	202	0.50	5.0	202	2	14.0	337	0.41	67	Arrival in conditions after a storm, only swell	LMS dynamic + MX-Lab
19		Departure	Night	7.7	15.0	270	1.80	8.0	202	1	12.0	337	0.41	247	Emergency scenario with full blackout.	LMS dynamic + MX-Lab
20		Arrival	Day	8.2	15.9	225	1.80	8.0	202	1	12.0	337	0.51	247	Average weather	LMS static + MX-Lab
21		Arrival	Late afternoon	8.2	15.9	225	1.80	8.0	202	1	12.0	337	0.51	247	Average weather	LMS static + MX-Lab
22		Arrival	Day	20.6	40.0	225	3.00	7.0	225	2	9.0	337	0.51	67	Severe Weather	LMS dynamic + MPS

Most runs have been executed with the prevailing environmental conditions: wind from SSW, sea waves from SSW, and swell waves from NNW (coming from). The current direction was varied between 067° and 247° (going to).

Preferably the e-SOV should approach the e-Tower in a heading equilibrium to the environmental conditions. On arrival, the vessel generally stopped at a distance of approximately 30 meters from the e-Tower center. The communication with the deckhand generally started at roughly 100m distance from the e-Tower. From there, the deckhand would guide the captain/pilot towards the e-Tower aiming to place the vessel bow underneath the tower boom tip and hold position.

Once in place, the deckhand would first grab the messenger/pick-up line for the hawser. Next he would attempt to grab the messenger/pick-up line for the electrical cable. Ideally, it is expected that both messenger lines will be grabbed at one go. However, if the vessel does not manage to hold position long enough, first the messenger line for hawser is grabbed. Following that, the vessel may need to approach again to grab the messenger line for electrical cable. Once both the messenger lines are on deck and secured (connected to a second messenger leading to the mooring deck), the vessel would move slightly astern and stabilize. During this period, lowering and winching of the hawser line may happen in parallel as well. Once the hawser is connected (confirmed by the deckhand) and the vessel is relatively stable, lowering and winching of the electrical cable takes place.

The e-SOV was free to weathervane after the charging line connection was established. The entire process took roughly 10 minutes. The deckhand is dismissed after the charging cable is connected. To make it easier for the captain to stay in position, distance rings at 30m, 40m and 50m were added to the ENC (Figure 3-7) in the simulations. The vessel captain also had a CCTV visual of the mooring deck available showing whether the connections have been established. The deckhand was also visible to the captain from the vessel bridge either as an avatar on the forecastle (Figure 3-8) or through the CCTV if s/he was in the mooring deck.



Figure 3-7: Distance rings around the E-tower

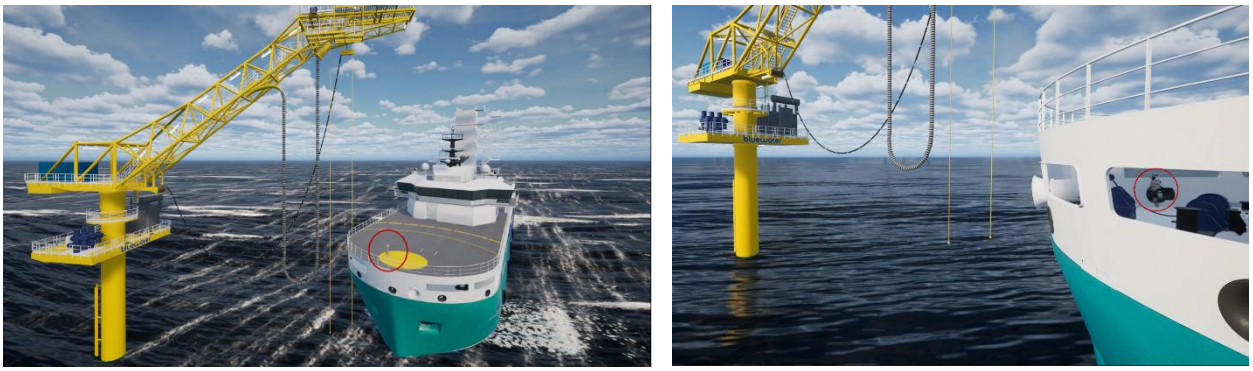


Figure 3-8: Avatar (circled in red) mirroring the deckhand (wearing the VR setup) on the bow (heli deck-left and mooring deck-right) of the vessel.

During departures, the charging cable is first disconnected and winched out. Following that, the hawser line is released and winched out. A deckhand is expected to execute the release from the mooring deck. However, in case of emergency, instant automated disconnection is also a possibility in the current design.

In most cases, the departure simulations stared with the e-SOV in equilibrium position with the environment. After starting the simulation, the captain continued to weathervane on the hawser for roughly 5-10 minutes, depending on the weather input. After that, the charging cable and the hawser line were disconnected. The captain would then use the thrusters and the environment to drift away from the e-Tower. The runs were terminated soon after the vessel reached roughly 500m distance from the e-Tower.

The emergency scenarios mostly involved regular departure scenarios with necessity to abort or perform task with reduced availability of resources. The emergencies were mostly triggered while the simulation was running.

4 PRESENTATION AND DISCUSSION OF THE RESULTS

4.1 Presentation of the results

The results of the simulations are presented in track and data plots.

The track plots shows the position of the ship during the run at regular intervals of 90 seconds. The arrows on the track plots indicate the current direction (also mentioned at top right corner). The box window (in red frame) mentions the environmental properties recorded during the simulation, at the time when the screenshot was taken. Figure 4-1 shows the track plot of Run 17. The track and data plots of all runs are included in APPENDIX 3.

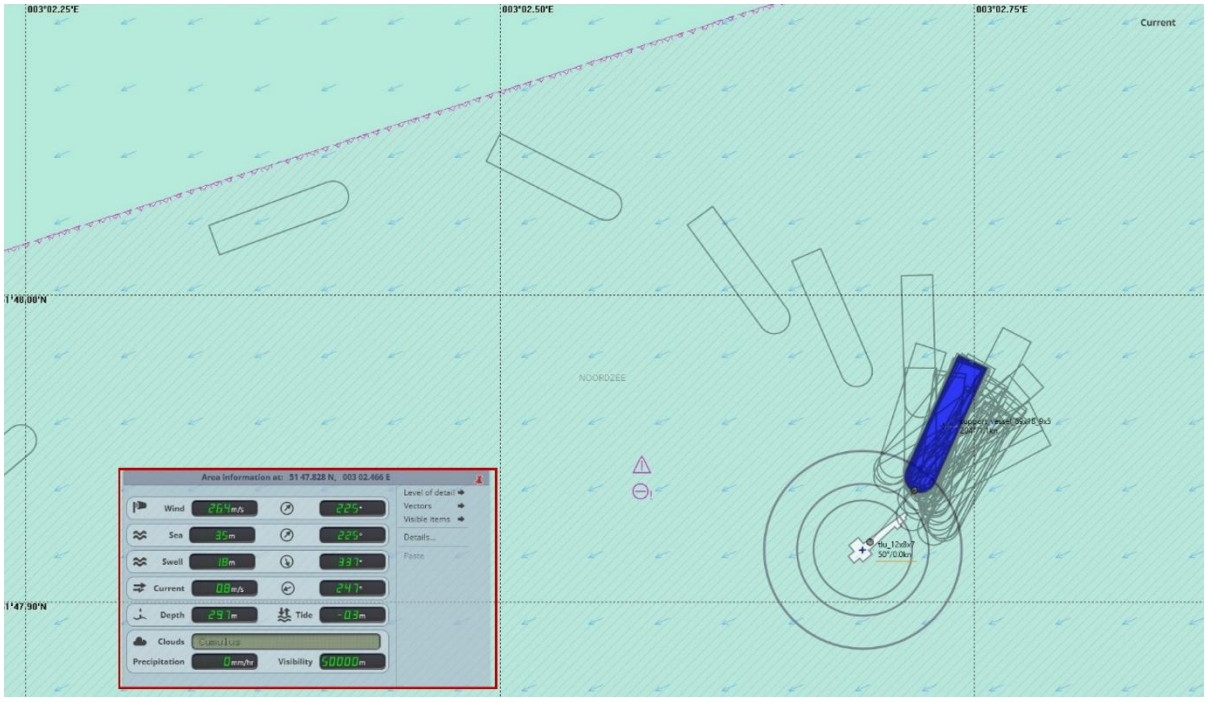


Figure 4-1: Track plot Run 17 (cropped)

The data plots show the values of selected parameters during the run and include the following plots:

a. Data plot showing metocean parameters as function of time:
   - Wind speed and direction (m/s and °N coming from),
   - Current speed and direction (m/s and °N going to),
   - Sea-wave height (significant wave height) and direction (m and °N coming from),
   - Swell-wave height (significant wave height) and direction (m and °N coming from)

b. Data plot showing speeds and heading of the e-SOV as function of time:
   - Longitudinal (forward) speed; through the water and over the ground (STW and SoG, in knots)
   - Transverse (lateral) speed; fore, mid and aft (knots, positive is to port),
   - Rate of turn (°/min, positive RoT is to starboard).
   - Heading (°N)

c. Data plot showing the use of e-SOV thrusters as function of time:
   - Aft thruster angles (°, positive is to starboard)
   - Aft thruster revolutions (rpm)
   - Bow thruster revolutions (rpm)
   - Bow thruster angles (°, positive is to starboard)

d. Data plot showing hawser tension and e-Tower heading:
   - Hawser load (tons)
   - e-Tower heading angle (deg, relative to global north)

e. Data plot showing motions of the vessel as function of time (together with RMS values):
   - Heave (m)
   - Roll (°, positive to starboard)
   - Pitch (°, positive is fore down)

f. Data plot showing accelerations at the bridge and bow of the e-SOV as function of time (together with RMS values):
   - Vertical acceleration bridge (m/sec^2)
   - Lateral acceleration bridge (m/sec^2)
   - Vertical acceleration bow (m/sec^2)
   - Lateral acceleration bow (m/sec^2)

Examples of plot c and d are shown in Figure 4-2.

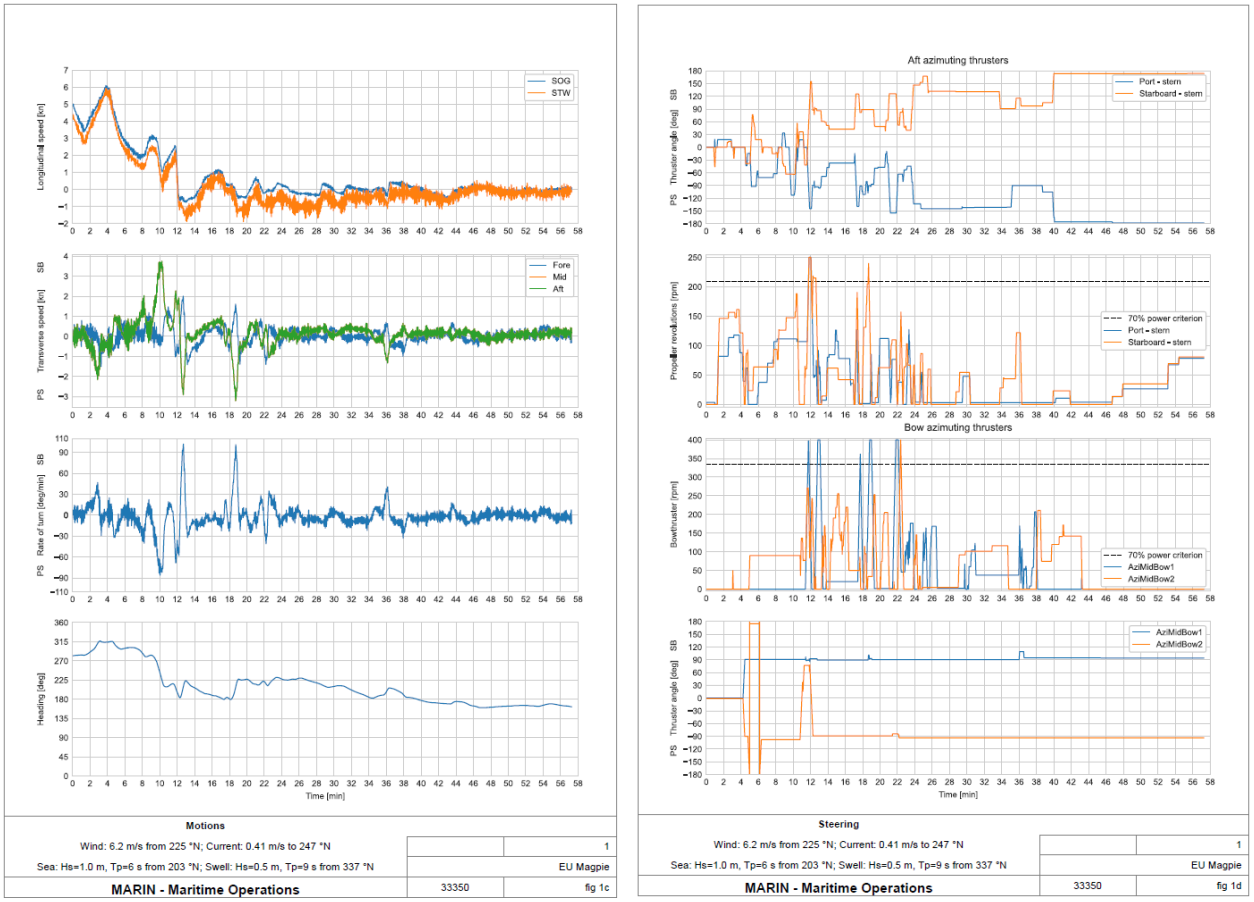


Figure 4-2: Example of data plot c and d

4.2 Evaluation criteria

4.2.1 General

The general philosophy for evaluating manoeuvres with respect to operational limits is that under normal operational conditions sufficient margin must be available to cope with unexpected events, such as wind gusts, human (steering) error etc.

The evaluation of the simulations includes a numerical analysis of:

- controllability of the vessel;
- hawser tension;
- roll and acceleration of the vessel.

The analysis is combined with the evaluation of the simulator instructor and captains executing the runs to an overall judgement regarding the safety and feasibility of each run.

4.2.2 Controllability

To assess the controllability of a manoeuvre, the use of the steering means of the vessel is evaluated: main propulsion and bow thruster, is there sufficient margin to cope with unexpected events. During a manoeuvre it can sometimes be necessary/convenient to use high power for a short period, e.g. give a short kick with the engine and full rudder to initiate a turn. Therefore a combined criterion of magnitude and duration is used. For large sea-going vessels, a typical duration for such normal use at high power is 1 minute.

Main propulsion

Typically, steering index criteria is used for evaluating controllability of a manoeuvre, which evaluates both the used propeller rpm and rudder angle together for any moment in time. However, the steering index is not applicable to vessels steered with azimuthing thrusters, such as the e-SOV. In these cases, the force of the thruster should not exceed 70% of their nominal capacity for more than 1 minute. As the force is proportional to the square of the propeller revolutions, the propeller rpm should not exceed 83.7% of the maximum propeller rpm. The e-SOV has thrusters with 250 rpm as maximum, thus, following the limit, the thrusters should not exceed 210 rpm. The ratings for evaluation of the applied azimuthing thruster forces are shown in Table 4-1. The e-SOV has two azimuthing stern thrusters. The evaluation is performed by assessing the rpm of both thrusters at any given moment. Thus, the power reserve is marked as insufficient if both thrusters are used above the 70% limit for a minute together.

Table 4-1: Criteria for main propulsion use

Rating	Score	Explanation
Ample reserves	+	The applied thruster force was less than 70% of the available thruster force during the entire run
Just sufficient reserves	+/-	The applied thruster force was more than 70% of the available thruster force for less than one minute
Insufficient reserves	-	The applied thruster force exceeded 70% of the available thruster force for more than one minute.

Bow thrusters

The e-SOV is equipped with two in-line bow thrusters. To have some margin for error and safety, the thrusters should not be used at maximum capacity for a prolonged time during the considered manoeuvre. The force of the thruster should not exceed 70% of their nominal capacity for more than 1 minute. As the force is proportional to the square of the propeller revolutions, the propeller rpm should not exceed 83.7% of the maximum propeller rpm. The ratings to evaluate the applied thruster force are shown in Table 4-2. In this study, the bow thruster has a max rpm of 400, thus the limit is set at 335 rpm.

Table 4-2: Ratings for the evaluation of the applied thruster forces

Rating	Score	Explanation
Ample reserves	+	The applied thruster force was less than 70% of the available thruster force during the entire run
Just sufficient reserves	+/-	The applied thruster force was less than 70% of the available thruster force for less than one minute
Insufficient reserves	-	The applied thruster force exceeded 70% of the available thruster force for more than one minute.

For overall evaluation, available reserve at all thrusters (bow and stern) are considered.

4.2.3 Hawser tension

Regarding the hawser line, the tension in the line is the constrain.

For the assessment of the used hawser tension, the following criteria is applied: the hawser tension may not exceed 20% of the NWBS (60 tons) more than 3 times in one hour and also may not exceed 25% of NWBS (= 75 tons) at any time.

Rating	Score	Explanation
Safe	+	Hawser tension below 60 tons
Doubtful	+/-	Hawser tension exceed 60 tons but not more than 3 times
Unsafe	-	Hawser tension exceed 75 tons more than 3 times or hawser tension exceeds 100 tons

The limits mentioned above is the general criteria applied by MARIN. Different values may be set by the hawser designers as safe working loads.

4.2.4 Roll and acceleration

For the required manned operation of connecting the hawser and electrical cable to the vessel, a deckhand has to be present on the foredeck (or mooring deck) of the e-SOV and perform specific tasks. For safety of the crew, ship movements need to stay within acceptable limits. In a study executed by Nordic Co-operative Organization for Applied Research (NORDFORSK), in 1987, workability criteria have been defined for working at sea [Ref 2.]. These criteria comprise roll, lateral accelerations and vertical accelerations criteria which are summarized in Table 4-3. It may be noted that the difference between heavy and light manual work is not clearly defined. Information on acceptable duration of such environments (for crew at work) is also not mentioned. The RMS values reported in the analysis are computed for the entire duration of the simulations, which continued for roughly 45-60 minutes in case of arrival and 10-15 minutes in case of departure simulations. Information regarding transit has been added for reference only and has not been used for the evaluation.

Table 4-3: Workability criteria and corresponding rms values, (NORDFORSK 1987).

Criteria	Intellectual work	Heavy manual work	Light manual work	Transit Passengers
Roll [deg]	3	4	6	2.5
Lateral acceleration [g] / [m/s^2]	0.05 / 0.49	0.07 / 0.69	0.10 / 0.98	0.04 / 0.39
Vertical acceleration [g] / [m/s^2]	0.10 / 0.98	0.15 / 1.47	0.20 / 1.96	0.05 / 0.49

While the limits are clearly defined, it is challenging to couple them directly with safe or unsafe working conditions. Thus, for the assessment of roll and acceleration the following rating is applied:

Table 4-4: Rating workability, in rms value.

Criteria			Score	Rating
Roll	*Lateral acceleration*	*Vertical acceleration*		
<4 deg	< 0.69 m/s^2	< 1.47 m/s^2	+	Below limit
4 – 6 deg	0.69 m/s^2 – 0.98 m/s^2	1.47 m/s^2 – 1.96 m/s^2	+/-	At the limit
> 6 deg	> 0.98 m/s^2	> 1.96 m/s^2	-	Over limit

While pitch motion is also an important safety and comfort aspect for the crew, guidelines in this regard was not found in the NORDFORSK references. The North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG) 4154 (NATO 2000) provides some reference for this case (Table 4-5). However, influence of pitch motion are heavily dependent on vessel length and associated accelerations, and recommended limits may not be valid for vessels of all lengths. As such, vertical accelerations probably provide a better estimate regarding pitch induced motions, rather than the pitch time history. Keeping this in mind, although pitch time history and RMS values are shown in the results, pitch response has not been included in the evaluation.

Table 4-5: Workability criteria (NATO 2000)

Criteria	Limit	Location
	Root mean square (RMS)	
Roll	4°	
Pitch	1.5°	
Vertical acceleration	1.96 [m/s^2]	Bridge
Lateral acceleration	0.98 [m/s^2]	Bridge

4.2.5 Assessment by captains and instructor

The captains assessed each run and commented on it, by means of a questionnaire (see Figure 4-3). With help of these comments, the conclusions and recommendations are supported. The instructor (master mariner from MARIN) also logged his observations regarding the run, which also served as an important evaluation criteria.

The ranking of the results of each run is based on the experience of the captains and instructor, considering comparable situations in real life.
The ranking is as follows:

- Safe (+);
- Doubtful (+/-);
- Unsafe (-).

At the end of each simulation, the deckhand was also interviewed regarding the practically of the performed operation and observations were noted by the human factor team of MARIN. Results from the human factor side are presented in a separate section.

4.2.6 Overall assessment

Based on the results of the numerical analysis and the feedback from the instructor and captains, an overall assessment is made of the safety level of each simulation run from the vessel handling or manoeuvring perspective. Hereby the following ranking was used:

- Safe (+);
- Just acceptable/On the limit (+/-);
- Unsafe (-).

The following definition for safe is used: “During the manoeuvre, the controllability was good with sufficient reserves available. Sufficient distance was kept towards navigation dangers to cope with unexpected events. In general, the manoeuvre was experienced as well feasible.”

In case of evaluating emergency scenarios, general safety margins are not considered and concentration is given only on vessel’s capability in averting collision or adverse situations.

Project 33350

Questionnaire for the pilot; to be filled in after each run

General info:
Filled in by:

Date:

Local time: …….

Scenario: Arrival / Departure Wind: …..

Run no: …….

Expert opinion for criteria:

General impression of run: Safe / doubtful / unsafe

Controllability of vessel during manoeuvre: Good/ doubtful / bad

Margins on steering controls: Good/ doubtful / bad

Margins on tugs: Good/ doubtful / bad

Berthing lateral speed: Safe / doubtful / unsafe

Remarks (if any and/or if applicable):

Regarding vessel velocity:

Regarding safety of tugs:

Other remarks:

Figure 4-3: Example of a questionnaire

4.2.7 Overview table with evaluation of results

In the discussion of the runs, an overview is given in a table, which presents the analysed results per run. The following information is provided:

Table 4-6: Example of run evaluation table

Run	manoeuvre	Environment	Run Description	Controllability		Hawser Tension [tons]	Workability			Captain Rating	Instructor Rating	Overall Rating
		[deg / m/s / m]		Stern Thrusters	Bow Thrusters		Roll [rms]	Lateral Acc. [m/s2]	Vert. Acc. [m/s2]			
1	Arrival	Wind: 225°/6.2 Sea: 203°/1.0 Swell: 337°/0.5 Cur: 247°/0.41	Familiarization run; mild conditions; with inactive motion base	+/-	+/-	+	+	+	+	+	+	+

Column 1: Run number.
Column 2: Arrival or departure run.
Column 3: Environmental conditions. Wind and current speed in m/s, sea and swell Hs in m, all directions in degrees. The direction for wind and waves represent direction they are coming from, whereas, direction for current represents the direction current is going to.
Column 4: Short run overview
Column 5: This reflects the numerical assessment of the used stern ASD thruster power. The following rating has been used:

+	Ample reserves
+/-	Just sufficient reserves
-	Insufficient reserves

Column 6: Here the assessment of the bow thrusters are given. The same rating system as for the stern thrusters.
Column 7: Provides the assessment of the hawser line tension.
Columns 8, 9, & 10: This is the evaluation of the motion behaviour of the vessel. The tug and the barge have identical roll motion. As for vertical and lateral accelerations, they were measured both at barge bow and tug bridge. However, for all the runs, accelerations at both locations were found to be below limit. Thus, they have been presented together here. The following rating has been used:

+	Below limit
+/-	At the limit
-	Over limit

Column 11: Evaluation of the run by the pilot/captain executing the manoeuvre. The following rating was used:

+	Safe
+/-	Doubtful
-	Not safe

Column 12: Evaluation of the run by MARIN's simulator instructor observing the manoeuvre. The following rating was used:

+	Safe
+/-	Doubtful
-	Not safe

Column 13: Overall evaluation of the run, taking into account the numerical criteria and the judgment of the pilots and instructor. The following rating was used:

+	Safe
+/-	Just acceptable/On the limit
-	Not safe

4.3 Discussion of the results

Results from the simulations have been discussed in the following three sub-sections: arrival, departure, and emergency runs.

4.3.1 Arrival runs

Table 4-7 summarizes the analysis of the arrival runs.

Table 4-7: Analysis of the arrival runs

Run	manoeuvre	Environment	Run Description	Controllability		Hawser Tension [tons]	Workability			Captain Rating	Instructor Rating	Overall Rating
		[deg / m/s / m]		Stern Thrusters	Bow Thrusters		Roll [rms]	Lateral Acc. [m/s2]	Vert. Acc. [m/s2]			
1	Arrival	Wind: 225°/6.2 Sea: 203°/1.0 Swell: 337°/0.5 Cur: 247°/0.41	Familiarization run; mild conditions; with inactive motion base	+/-	+/-	+	+	+	+	+	+	+
2	Arrival	Wind: 202°/6.2 Sea: 202°/1.5 Swell: 337°/1.0 Cur: 67°/0.41	Familiarization run with active motion base, increase in wind speed during simulation.	+	+	+	+	+	+	+	+	+
4	Arrival	Wind: 225°/7.7 Sea: 202°/1.5 Swell: 337°/0.5 Cur: 67°/0.41	Mild environment; 60m hawser	+	+/-	+	+	+	+	+	+	+
5	Arrival	Wind: 247°/12.9 Sea: 247°/2.0 Swell: 337°/1.5 Cur: 247°/0.41	Arrival in moderate conditions, 60m hawser | 85% annual weather	+	+	+	+	+	+	+	+	+
7	Arrival	Wind: 225°/7.7 Sea: 202°/1.5 Swell: 337°/0.5 Cur: 67°/0.70	Mild environment with higher current; 40m hawser	+/-	+/-	+	+	+	+	+/-	+	+/-
8	Arrival	Wind: 247°/12.9 Sea: 247°/2.0 Swell: 337°/1.5 Cur: 200°/0.50	Arrival in moderate conditions; 40m hawser | 85% annual weather	+/-	+/-	+	+	+	+	+	+	+
10	Arrival	Wind: 225°/20.6 Sea: 202°/3.0 Swell: 337°/1.8 Cur: 67°/0.51	Arrival in severe weather | 94% annual weather	+/-	+/-	N/A	+	+	+	+/-	+/-	-
11	Arrival	Wind: 225°/20.6 Sea: 202°/2.5 Swell: 337°/1.8 Cur: 67°/0.51	Arrival in severe weather | 94% annual weather	+/-	+/-	-	+	+	+	+	+/-	-
15	Arrival	Wind: 290°/7.7 Sea: 290°/1.5 Swell: 337°/0.5 Cur: 67°/0.60	Mild weater, messenger grabbing from below deck.	+	+	+	+	+	+	+	+	+
16	Arrival	Wind: 337°/12.9 Sea: 337°/2.0 Swell: 337°/1.5 Cur: 67°/0.80	Moderate weather conditions, messenger grabbing from below deck.	+/-	+/-	+	+	+	+	+	+	+
17	Arrival	Wind: 225°/20.6 Sea: 202°/3.0 Swell: 337°/1.8 Cur: 247°/0.80	Arrival in severe weather | 94% annual weather	+	+/-	-	+	+	+	+/-	+	+/-
18	Arrival	Wind: 202°/4.1 Sea: 202°/0.5 Swell: 337°/2.0 Cur: 67°/0.41	Arrival in conditions after a storm, only swell	+	+/-	+	+	+	+	+	+	+

Run 1 was performed in mild environmental conditions with 1.0m (203°) waves, 0.5m (337°) swell, and 12 knots (225°) of wind, without an active motion base. A 0.8 knots flood current was introduced going towards northeast. This was also treated as a familiarization run for the pilot with a longer approach distance. The run was started with the e-SOV roughly 1.5 nautical mile from the e-Tower with an initial speed of 5 knots. The speed was gradually reduced while approaching closer to the tower, with the final speed oscillating around zero during the connection (Figure 4-4). The vessel made a controlled approach using guidance from the deckhand and stayed in position until the hawser and electrical cable messenger lines were picked-up. During the approach, for a brief instance, both of the stern thrusters exceed the 70% limit. The bow thrusters also exceeded the 70% limit at one instance. However, this was a familiarization run and some of the manoeuvres were performed for testing and familiarization, rather than out of necessity. In general, ample power reserve was available on the azimuth thrusters. During connection, motions observed at the deck were quite limiting and well within acceptable limits. After connection, hawser line tension remained mostly below 10 tons with no power being applied on

the thrusters. Considering safety of manoeuvre and available power reserve, the run has been marked as safe overall.

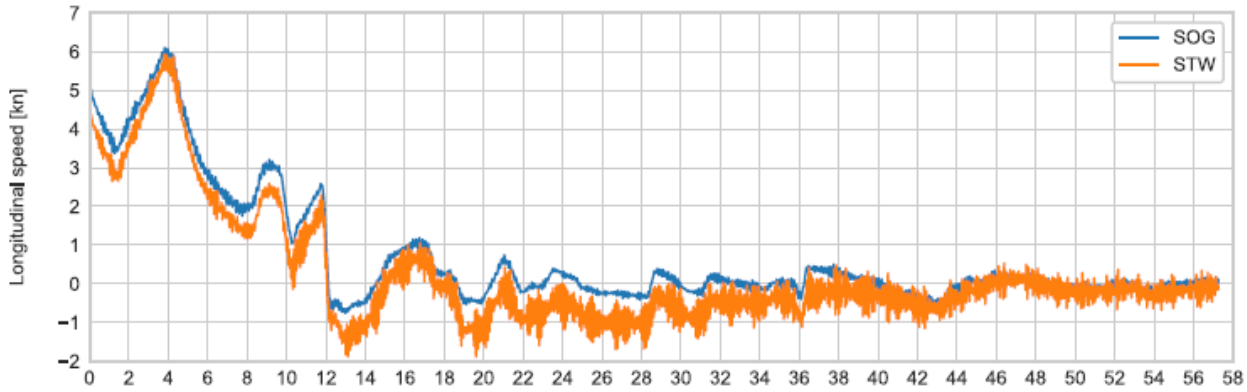


Figure 4-4: Longitudinal or forward speed of the e-SOV (speed over ground and speed over water), as measured during the simulation run 1.

Run 2 was also with mild environment (1.5m (202°) waves, 1.0m (337°) swell, 12 (202°) knots wind, and 0.8 knots ebb current going towards southwest), and was the first run with the motion base active. Starting speed for the vessel was around 5 knots, which was gradually brought down to less than 1 knots of speed over water during the final approach. During the simulation, one of the stern and one of the bow thrusters exceeded the 70% limit for brief periods (Figure 4-5). However, there was ample reserve power available through the other two thrusters. As such, the run is marked as green in terms of controllability. After hawser connection, some power was applied on the thrusters for re-alignment. This was reflected on the hawser line tension which went up to 20 tons. Wind and current from the same direction also made the residence relatively easier. The approach was safe and well controlled. Good communication was also maintained with deckhand during approach and connection.

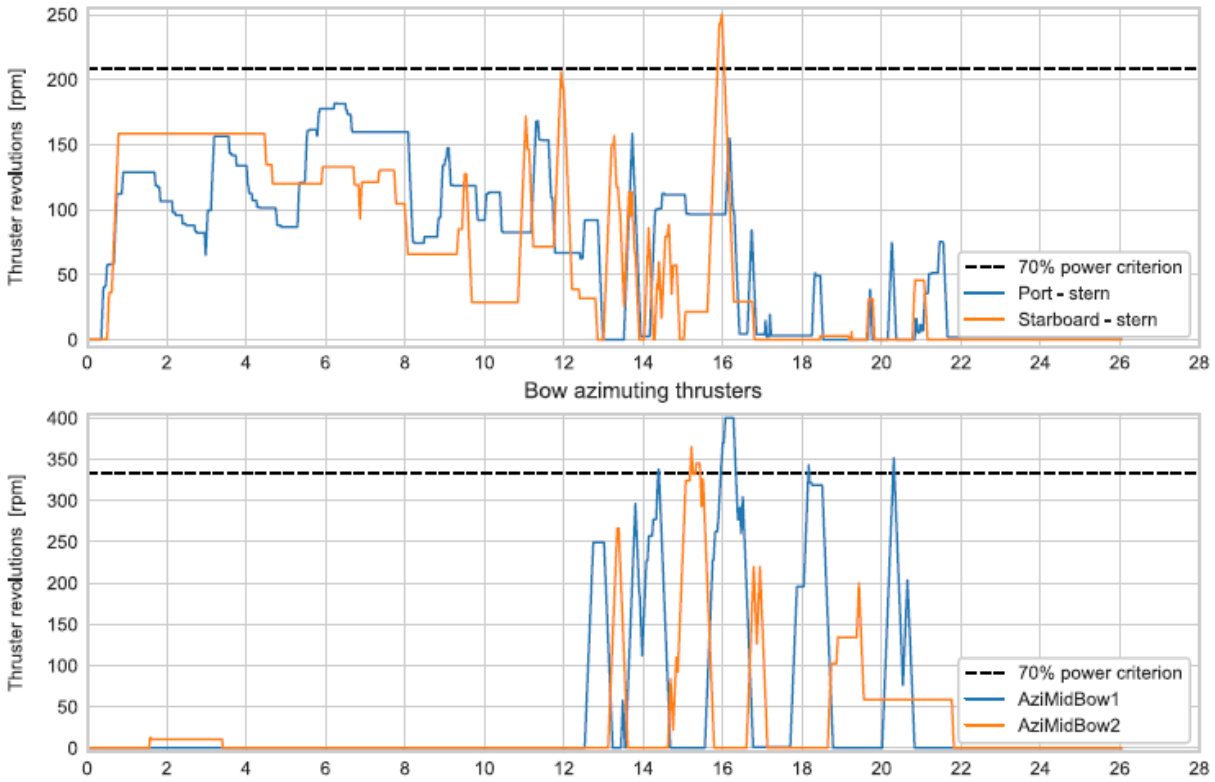


Figure 4-5: RPM of the stern (top) and bow (bottom) thrusters of the vessel, as measured during the simulation run 2.

Run 4 was the first night time simulation with the environment remaining relatively mild with wind speed of 15 knots (225°), wind waves of 1.5m (225°), swell of 0.5m (337°), and 0.8 knots ebb current. The simulation was started at roughly 1000m from the e-Tower with e-SOV at 5 knots forward speed. Use of stern thrusters were quite limited during the manoeuvre, with some sudden power bursts on bow thrusters. However, overall use of thrusters remained limited, ensuring sufficient overall reserve. The hawser tension peaked at 30 tons just after connection, and then stayed below 10 tons (Figure 4-6). The current direction and amplitude was changed while the vessel was connected to the hawser line. The captain preferred to keep station instead of weather vanning, resulting in a requirement of 20% rpm on stern thrusters.

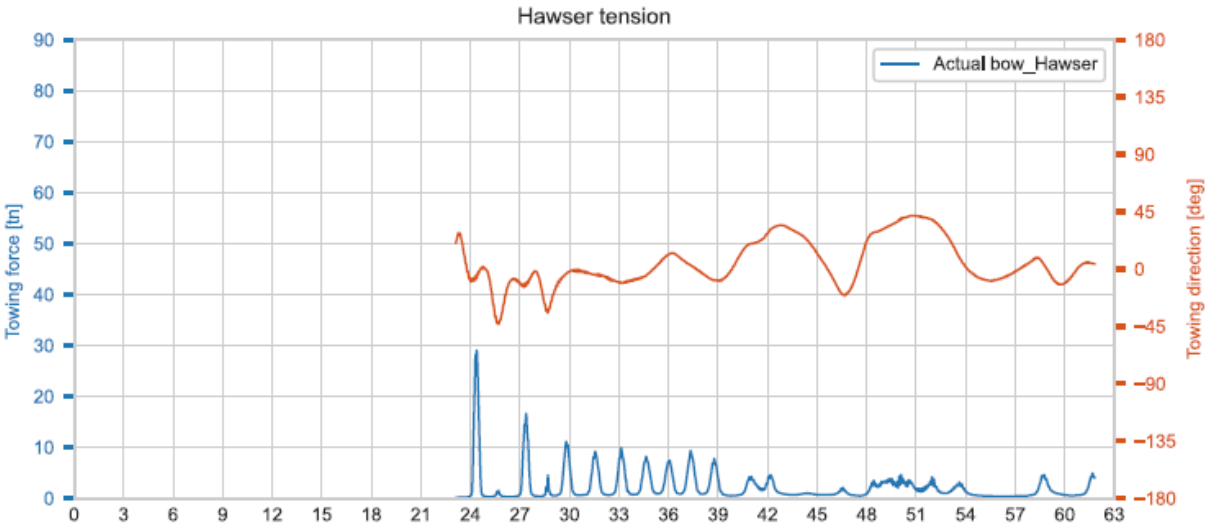


Figure 4-6: Hawser force and relative line direction to vessel heading, as measured during the simulation run 4.

In **run 5**, simulation were performed with moderate weather with 2.0m sea (247°), 1.5m swell (337°), 25 knots of wind (247°), and 0.8 knots ebb current. Initially, the sea waves were coming from the north north-west, which was later changed to the direction of west south-west in keeping with the wind direction. The approach remained mostly similar to previous cases. However, due to increased environment, grabbing the messenger lines became more challenging. In the first attempt, only the hawser messenger line was picked up. The vessel returned to position for a second time to pick up the messenger for the electrical cable. The return took roughly 10 additional minutes (Figure 4-7, first pick-up at around 11 mins and second at around 23 mins). A 60m hawser line was used (Figure 4-7). Both bow and stern thruster usage was limited with sufficient reserve available. The environmental directions also assisted with stability. After connection with a 60m hawser line, roughly 20 ton of force was observed on the hawser line. At a later stage of the simulation, to prevent yawing, initially 20% (of max thruster power) back thrust was applied at the stern thrusters, which was later increased to 40%. Even with 40% power on thrusters, the hawser load remained below 30 tons. However, preventing the yaw instead of weather vanning may not have been necessary. Overall, the run was rated as safe considering controllability, hawser tension, and workability.

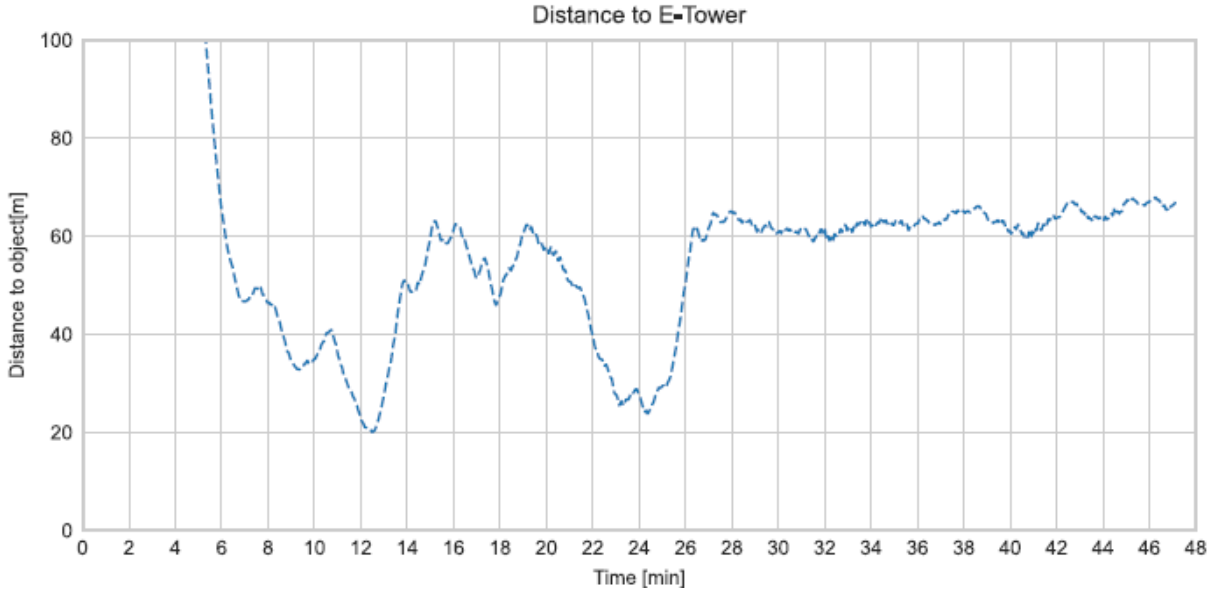


Figure 4-7: Stern thruster rpm (top) and hawser force (bottom) measured during the simulation run 5

Run 7 was a repeat run (with the VR setup on the LMS) with relatively mild environmental conditions of 1.5m sea (202°), 0.5m swell (337°), and 15 knots of wind (225°). However, the current was increased to roughly 1.4 knots (67°), which is close to the maximum current limits at the North Sea. With the high current, the first approach was not favourable. The second approach was more against the current, resulting in increased difficulties. The captain commented that the current was too strong for a safe approach. According to the captain, in such high currents, the preference would be to wait for slack tide to make the approach and connection, perform charging while on hawser, and then depart again with a slack tide. keeping the captain's comment in consideration, the run has been marked as doubtful. That being said, it was also concluded during debriefing that a safe manoeuvre may have been possible for the provided current given that an alternative approach was taken (taking longer to find a stable equilibrium and then approach, instead of heading for the boom direction). This has been confirmed in later simulations. Thus, the run remains doubtful if the preferred approach direction remains against the environment.

After the second approach attempt, the current was reduced to 0.6 knots, which allowed a safe approach and connection. During approach, both bow and stern thrusters crossed the 70% limit for brief moments. However, in general, sufficient controllability remained. After connection, tension on the line also remained low. Motions observed on the vessel were also quite limited. Track plot from the simulation is shown in Figure 4-8 for reference.

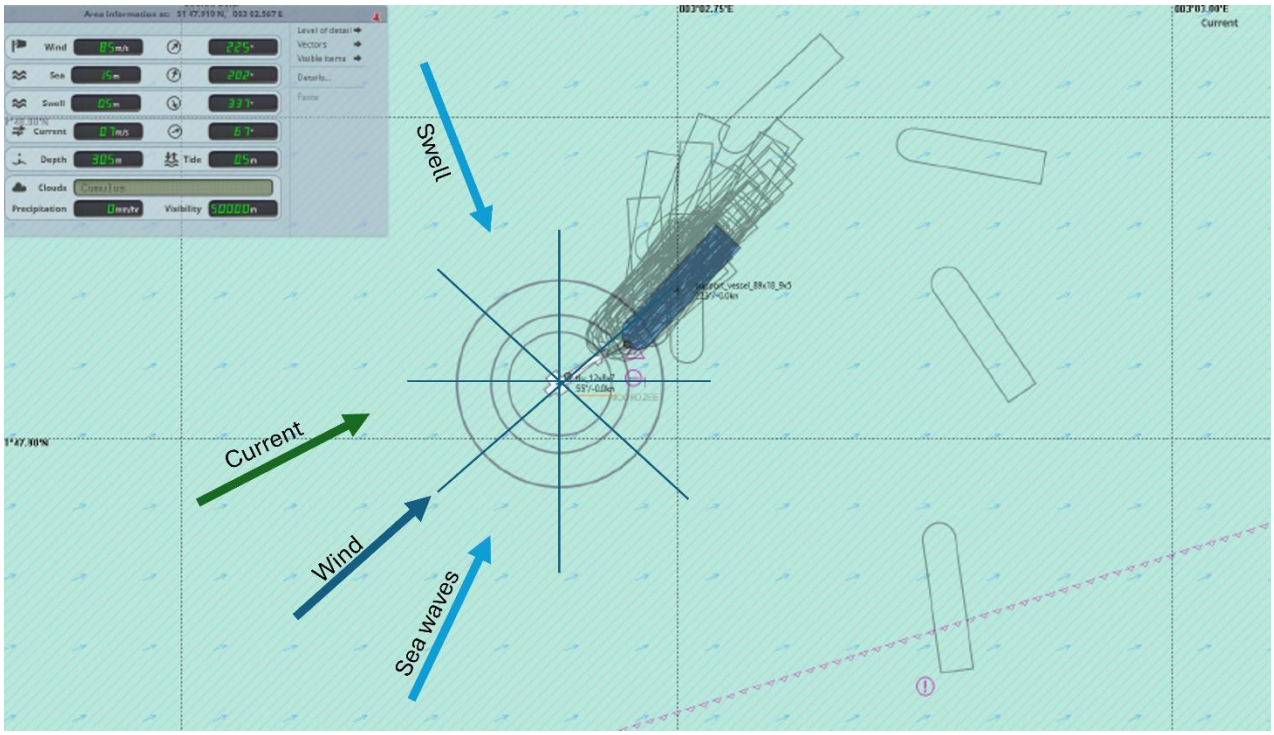


Figure 4-8: Track plot from the simulation run 7, edited by adding environmental directions for better clarity

R**un 8** was also a repeat run with the VR setup on the LMS, with 2.0m sea (247°), 1.5m swell (337°), 25 knots wind (247°), and 1 knot current (200°). During approach, the captain requested a e-Tower boom heading towards north (following the discussion in previous debriefing). During the turning of the vessel, the bow and stern thruster limits were exceed slightly. However, overall the manoeuvre remained safe. Just after connection, the hawser line load exceeded 45 tons, which later stabilized at below 30 tons, with the vessel weather vanning without using thrusters. The simulation environment covered 85% of the annual environment at the study location.

Run 10 was an arrival simulation in severe weather conditions with 3.0m sea (202°), 1.8m swell (337°), 40 knots wind (225°), and 1 knot current (67°). After starting, the captain requested a tower boom angle of 110 degree. After the approach, the captain remarked that the circumstances were not safe to proceed with deck operation. The wind was too high. The motion results also show notable roll and pitch on the vessel (Figure 4-9), with the pitch rms being very close to the limiting value. Thus, the approach was aborted and the simulation was terminated. Overall, the simulation has been marked as unsafe.

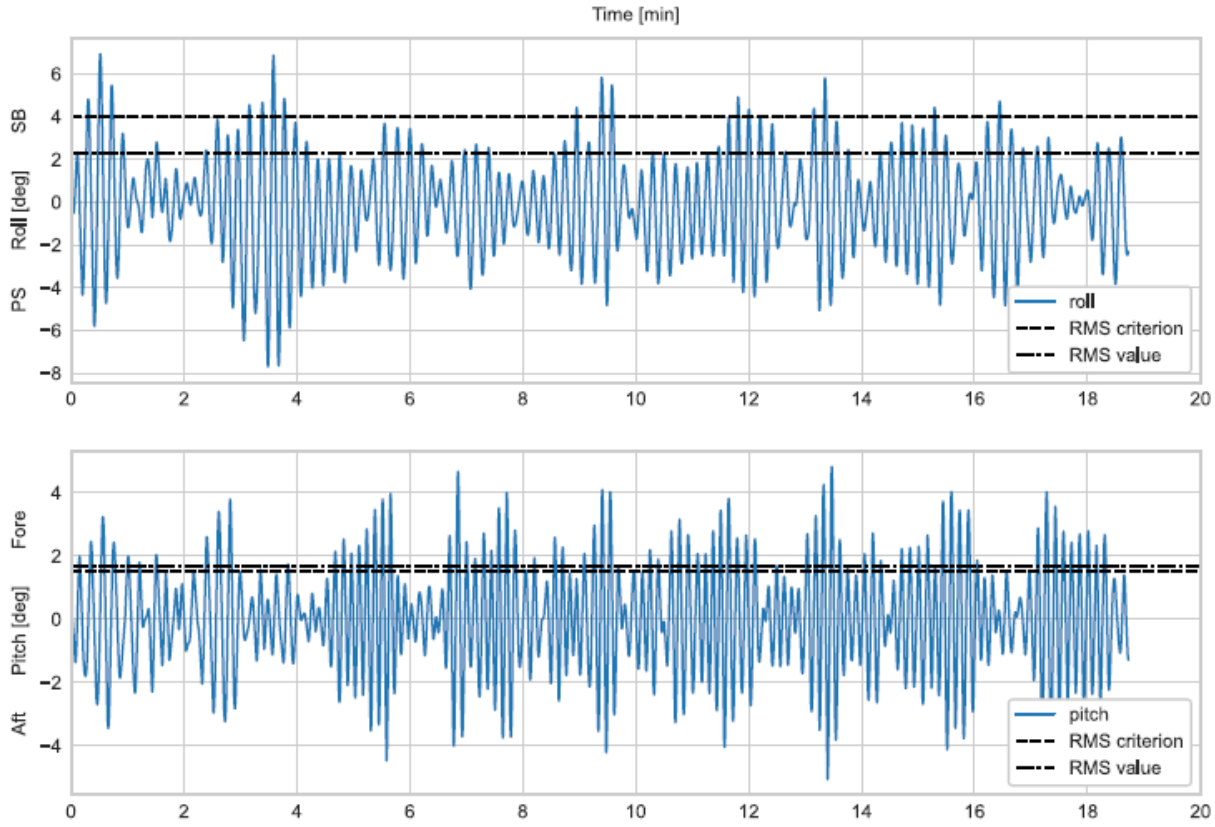


Figure 4-9: Roll and pitch motions measured at the e-SOV during the arrival run 10.

In **Run 11**, the previous conditions as run 10 was repeated with a slight reduction in the sea height of 0.5m. Like before, the captain requested a tower boom heading of 110 degrees and continued with the approach. Although all four thrusters onboard the vessel were used to perform the approach and do station keeping, the exceedance of safety margin remained for brief moments. During the approach, the deck hand reported discomfort due to severe motions. Experiencing the actual wind probably would have increased the discomfort, which was not possible to replicate in the simulator. With two attempts, the messenger lines were grabbed and connections were established.

After connection, the line load peaked at 60 tons and then gradually reduced to below 40 tons. Some fishtailing was observed on the vessel. To counter, roughly 100 rpm was applied on both stern thrusters, resulting in exceedance of the 75 ton load limit three times. However, maximum load remained below 100 tons. The power was brought down later to zero, resulting in a notably lower hawser loads. However, fishtailing is also a commonly observed phenomenon while the vessel in on anchor. As such, countering it may not be essential unless it affects the hawser and charging operation notably.

Considering the vessel controllability, hawser tension with vessel in back thrust, vessel motion and wind on deck, the run has been marked as unsafe.

Run 15 was a repeat run with relatively calm weather conditions, with the messenger lines being grabbed from the mooring deck. The sea was at 1.5m (290°) with swell of 0.5m (337°), wind of 15 knots (290°), and current of 1.2 knots (67°). Considering the environment, a boom direction of 67º was requested and the approach was done with a heading of roughly 260º. Considering the relatively calm weather and favourable approach strategy, all parameters of interest were within limits. Thus, the run has been marked as safe.

Since the deckhand operated from the mooring deck, the vessel approach was slightly adjusted to bring the messenger lines either at the starboard of port side. The deck hand expressed better comfort while

doing the operation from the mooring deck, being within a cover area and less exposed to the environment. However, he also mentioned less situational awareness due to less exposure. The necessity to have a pulling hook to bring in the lines was also mentioned. The hook will also extend deckhand's range in terms of required distance from the line.

Run 16 was performed in moderate weather condition with sea of 2.0m (337°), swell of 1.5m (337°), wind of 25 knots (337°) and current of 1.6 knots (67°). The manned operation was performed from the mooring deck. A boom direction of 67º was requested a while after the simulation started. The vessel first looked for equilibrium heading while being close to the tower and then made the final approach. The deckhand guided the bridge towards the pick-up/messenger lines. After the vessel reached an equilibrium on the hawser, the electrical cable was lowered and connected.

During the approach, both the bow and stern thruster limits were exceed for brief moments. After connection, the hawser load peaked at roughly 55 tons, and gradually reduced to below 10 tons after the thrusters were set to 0 rpm. To check motion stability, the stern thruster rpms were increased to 40%. Due to the back thrust, the lateral acceleration was slightly decreased, while the vertical acceleration slightly increased. In terms of roll and pitch motion, hardly any difference is observed. However, the back thrust increased the hawser load to roughly 25 tons.

Following the instructor, the approach was smooth. The captain also marked the run as safe without raising objection regarding the high current. As such, overall rating for the run was safe.

Run 17 was a repeat run of the severe weather (run 11) with the manned operation happening from the mooring deck. The boom angle was set to 45º, and the vessel approached with a rough heading of 200º. The captain made a controlled approach and took two attempts to grab both messenger lines. The vessel had a relatively large yaw when on hawser. Thus, a question was raised regarding whether a desired angle is to be maintained while connecting the electrical cable. Such limit will require use of thrusters to maintain heading. This will also increase load on the hawser line. If there are no such requirements, the vessel can weather vane on the hawser without back thrust, which also puts lower load on the hawser line.

In the severe weather, with 50% back thrust on stern thrusters, the tension on the hawser peaks at 90 tons. Without any back thrust applied, weather vanning in this weather remains a valid possibility. However, as before, the deckhand experienced discomfort due to motions and the wind remains too high to perform a comfortable line grabbing action. The run remains valid while assessed in terms of controllability or manoeuvring, however, the captain expressed doubts regarding the operation at give environment. Thus, the simulation has been marked as doubtful.

Run 18 shows arrival condition after a storm, with minimum wind and sea (8 knots, 0.5m from 202°), but relatively high swell of 2.0m (337°). The vessel managed a smooth approach without issues. The messenger lines were picked up in one attempt and the hawser and electrical cable were connected successively. The bow thrusters exceeded limits for brief moments. However, overall, the vessel remained well controllable with low hawser line loads. While the vessel was weather vanning, the current direction was changed to see the vessel response. The vessel did not show motions towards the tower. Overall, the run has been marked as safe.

4.3.2 Departure runs

Table 4-8 summarizes the analysis of the departure runs.

Table 4-8: Analysis of the departure runs

Run	manoeuvr	Environment	Run Description	Controllability		Hawser Tension [tons]	Workability			Captain Rating	Instructor Rating	Overall Rating
		[deg / m/s / m]		Stern Thrusters	Bow Thrusters		Roll [rms]	Lateral Acc. [m/s2]	Vert. Acc. [m/s2]			
3	Departure	Wind: 247°/7.7 Sea: 202°/1.5 Swell: 337°/0.5 Cur: 67°/0.51	Departure in mild weather after reaching steady state; 40m hawser.	+	+	+	+	+	+	+	+	+
6	Departure	Wind: 225°/12.9 Sea: 202°/2.0 Swell: 337°/1.5 Cur: 67°/0.41	Departure in moderate condition after reaching steady state; 40m hawser.	+/-	+	+	+	+	+	+	+	+
12	Departure	Wind: 225°/20.6 Sea: 202°/2.5 Swell: 337°/1.8 Cur: 247°/0.51	Departure in severe weather | 94% annual weather	+	+	+	+	+	+	+	+	+
13	Departure	Wind: 202°/15.4 Sea: 202°/2.8 Swell: 337°/1.5 Cur: 247°/0.31–0.60	Departure with increased sea and swell; 60m hawser	+	+	+	+	+	+	+	+	+

Run 3 was the first departure run and was performed in relatively mild conditions with 1.5m sea (202°), 0.5m swell (337°), 15 knots of wind (247°), and 1 knot ebb current. After the simulation started and the vessel was steady, first the electrical cable was disconnected, followed by the hawser line. The process took roughly 5 minutes. After the lines disconnected, the vessel moved backwards and away from the tower. It was a controlled run with all parameters of interest being within limit.

Run 6 was performed in moderate weather conditions with 2.0m sea (202°), 1.5m swell (337°), 25 knots of wind (225°), and 08 knots ebb current. Like the run before, first the electrical cable was disconnected and next the hawser line. The process took roughly 7 minutes and the vessel was weather vanning during this period without noticeable issues. The stern thrusters exceeded the 70% margin for a very brief period while moving away from the tower. This was not a maneuvering necessity and was simply done for a quick departure. Thus, overall, the run has been marked as safe.

Run 12 was a departure simulation in severe weather with 2.5m sea (202°), 1.8m swell (337°), and 40 knots of wind (225°). The current was 1.0 knot (247°). With the rough weather, tension on the 40m hawser line was higher and was peaking close to 60 tons. The vessel showed slight fishtailing, thus, some power was applied for brief periods to realign. However, overall thruster usage was quite limited. Pitch motion on the vessel was notably high. Vessel controllability and workability on the mooring deck was measured as safe following the set limits. Although uncomfortable, the deckhand commented the disconnection to be possible from the mooring deck. The run suggest that the vessel is sufficiently powered and capable of a quick departure in rough weathers, if necessary.

Run 13 was a similar run to the previous one (12) with 2.8m sea (202°), 1.5m swell (337°), 30 knots of wind (202°), and max 1.2 knots current (247°). A 60m hawser line was used in this simulation. The simulation was started with a 0.6 knots of current, which was gradually increased to 1.6 knots in 10 minutes. The run focused more on observing the weather vanning behavior of the vessel, rather than performing the departure maneuver. Thus, departure happened roughly 20 mins after the start of the simulation. All considered parameters were within safe limits.

The captain kept the bow thrusters in use during the simulation to maintain heading control and reduce fish tailing. Some back thrust was also used during brief periods, which resulted in increased hawser tension. Once in equilibrium and if excessive fishtailing is not observed, probably weather vanning on the hawser is the most convenient option during the station keeping/charging.

4.3.3 Emergency runs

Table 4-9 summarizes the analysis of the emergency runs.

Table 4-9: Analysis of the emergency runs

Run	manoeuvr	Environment	Run Description	Controllability		Hawser Tension [tons]	Workability			Captain Rating	Instructor Rating	Overall Rating
		[deg / m/s / m]		Stern Thrusters	Bow Thrusters		Roll [rms]	Lateral Acc. [m/s2]	Vert. Acc. [m/s2]			
9	Departure	Wind: 225–340°/14–15.4 Sea: 202°/2.8 Swell: 337°/1.3 Cur: 247°/0.60	Emergency departure while charging due to changed weather; wind shift	+	-	+/-	+	+	+	+/-	+	+
14	Departure	Wind: 225°/4.1 Sea: 225°/1.5 Swell: 202°/1.0 Cur: 135°/0.80	Emergency scenario with half-blackout | 1 bow & 1 stern thruster.	+/-	+	+	+	+	+	+	+	+
19	Departure	Wind: 270°/7.7 Sea: 202°/1.8 Swell: 337°/1.0 Cur: 247°/0.41	Emergency scenario with full blackout .	N/A	N/A	+	+	+	+	+	+	+

Run 9 involved relatively rough weather conditions with 2.8m sea (202°), 1.3m swell (337°), 30 knots of wind (225°-340°), and 1.2 knots flood current. The simulation started as a station keeping exercise with changing wind conditions (speed and direction). The stern thrusters were operated at 40% power to maintain directional stability and keep the vessel clear from the tower. With the back thrust, the hawser tension peaked up to 70 tons. Considering the required amount of back thrust and tension on the line, the captain decided for an emergency departure. The deckhand also expressed discomfort regarding being on deck is such weather.

The bow thrusters exceeded the limit after the release of the hawser, while moving away from the tower. Using both thrusters at max rpm for that period was choice from the captain but not a necessity from maneuvering perspective. The captain also commented that he was doubtful regarding prolonged station keeping in that weather. However, he observed the departure to be safe. Also, in case of emergency runs, the limits are not applied and only safe departure from site is assessed. Thus, overall, the run has been marked as safe.

Run 14 started as a station keeping exercise with a 40m hawser line. The sea was 1.5m (225°), swell 1.0m (202°), 15 knots of wind (225°), and 1.6 knots current (135°). The vessel was stable with both minimum and no power at the stern thrusters. Application of the bow thruster helped with reduction of roll motion, however, was not essential to use. As expected, application of back thrusters increased the hawser line tension, but the line tension remained below 40 tons. The vessel prepared for departure by initially releasing the charging cable. Just after the release of the hawser, a partial failure was reported with only one bow and one stern thruster working. The vessel showed sufficient redundancy in power for a safe departure.

An exception in vertical acceleration recording was observed in the simulation. This should be disregarded.

Run 19 was a departure simulation that started with station keeping in relatively mild weather conditions with 1.8m sea (202°), 1.0m swell (337°), 15 knots of wind (270°), and 0.8 knots flood current. For the first 11 minutes of simulation, the vessel managed to keep station with ease with no or minimum power applied to the thrusters. Tension on the hawser line also remained low. For departure, initially the electrical cable was disconnected, followed by the hawser line. After disconnecting the hawse, a full blackout was introduced. Since the vessel was disconnected, it continued to drift with a heading towards the nearby wind turbine. To avoid collision, the captain asked to drop anchor. Vessel stopped drifting after dropping anchor and the simulation was terminated.

4.3.4 Overall observations

- In general, for the simulated conditions, the e-SOV proved to have sufficient power to perform arrival, residence, and departure maneuvers safely. Even with partial failure of one stern and one bow thruster, the vessel managed to safely depart in the simulations (for the given environmental conditions). Considering only the maneuvering aspect, almost all runs were commented as safe by the simulator instructor and the captains. However, it was commented that the situation becomes more challenging with wind above 40 knots, and combination of waves and swell above 2.5m and 1.5m.

- In theory, because of the rotatable boom of the e-Tower, even in severe circumstances, navigating to a position close to the boom in order to pick up the messenger lines should be possible. However, extreme weather also comes with additional challenges like less efficiency of thrusters, green water, and crew safety during deck operations.

- The design load of the hawser line proved sufficient for almost all simulations, except for the ones where back thrust was applied in severe weather conditions. In general, the observation was that unless the environment pushes the vessel towards the tower, it is better to weather vane without back thrust. However, if excessive fish tailing is observed during weather vanning, some back thrust may be necessary.

- No notable difference was observed between the 40m and 60m lines, except that slightly less fish tailing was reported for one of the simulations with 60m line. The hawser line tensions recorded during the simulations are also heavily dependent on the integration solver and simulation time step, and may not always be very accurate considering the real time performance requirement at the simulator. Typical observation is that the estimates are conservative compared to fast-time simulations with Dynamic Mooring Analysis. Thus, fast-time simulations are recommended for finalizing the design load and length for the hawser line.

- Except for the severe weather conditions, the deckhand experienced relatively comfortable working conditions in most cases. The deck hand also expressed preference towards working from the mooring deck, in a closed and safe environment, rather than working from the open and exposed top deck. However, he also admitted that working from the mooring deck gave him less situational awareness.

As a general observation, following regulations, vessels operating in wind parks are obliged to have a DP system onboard. Thus, the operating captains/pilots are also more used to a DP based approach, which focuses more on station keeping, rather than free weather vanning with the environment. As such, without prior training, performing such manual approach and departure maneuvers for charging operations may prove somewhat challenging (or maybe even a bit frustrating) for the pilots/captains. This was also observed during the 3-day simulation campaign where the captains showed notably higher comfort level in performing the maneuvers on the 3rd day of the simulation. As such, even for highly experienced captains/pilots, sufficient prior training would be recommended before deploying them to perform the maneuvers at sea.

4.4 Human Factors Methods and Observations

For the human factors part of the study, the focus was on assessing the feasibility of the E-tower operation from a deck perspective. This is important because deck operations during offshore charging involve close proximity to infrastructure, exposure to environmental conditions, and coordination with other operational roles. These factors can introduce potential safety risks.

The methodology consisted of observations during simulator-based walkthroughs, supported by semi-structured interviews with participants. The participants were asked to give feedback on the operational procedure as well as on their feeling of comfort and safety.

Prior to the simulations, the deckhand/s were given a background questionnaire to collect data about his/their previous experiences. This questionnaire can be found in 0.

4.4.1 Results

Throughout the three test days two participants with deck experience observed the E-tower operation in VR and gave feedback on operational procedures and safety. On the first test day participants experienced the VR without motions above deck. On the second test day the participants experienced the VR with motions above deck. And on the third test day they experienced it without motions below deck. Therefore, the first and last test day had stronger focus on operational procedures while the second more on feelings of comfort and safety.

4.4.2 The operation

In the discussions during and after the simulation runs it was concluded that 4 to 5 people on deck are needed to execute the operation safely and efficiently:

- 2 people above deck, one focuses on the communication and supervision and the other focuses on grabbing the lines and connecting.
- 2-3 people below deck, one focuses on communication and supervision and one or two focus on pre-rigging and connecting.

The steps in the operation from deck perspective were observed and discussed as follows:

1. The deck officer above deck communicates over radio with the bridge to agree upon it on which side of the pick-up lines the vessel will approach. *In the simulator runs the communication about the plan was not always clear. This was mentioned as important by the participants for ensuring the safety and efficiency of the operation.*
2. The deckhands prepare for the operation by ensuring the ropes are ready to attach the pick-up lines. *As a safety measure both the starboard as well as the port side could be prepared in case the initial plan cannot be executed due to environmental conditions*.
3. Upon closer approach the deck officer above deck communicates over radio the estimated distance from the pick-up lines to the bridge.
4. HEHW and CEHW are lowered. *Discussions were not fully conclusive on where this task should be allocated. The benefit of allocating it on the deck is that they have a closer view on the operation. However, this does require a dedicated person. Optionally, the deck officer can simply instruct the bridge on when and how much to lower it.*
5. The deck officer above deck communicates to the bridge that the lines are in reach. The deckhand above deck grabs the lines. *In discussions it was indicated that the vessel has to stay in stable position for 5-6 minutes to be able to finish the connection phase. The participants marked this as the most critical part of the operation, because sudden forces during connection could injure the deckhands if the operation is not closely coordinated. Clear and strict protocols should be into place.*
6. The deckhands below deck attaches the lines. The hawser gets connected and tensioned first whereafter the power cable is connected. The deck officer below deck supervises this to ensure safety.
7. The deckhands above and below deck clean up and prepare everything for departure.

4.4.3 Comfort and safety of motions

Throughout the three test days participants generally indicated to feel safe and comfortable executing the operation both above as well as below deck and both in night as well as day conditions. Run 9 and run 12 on the second test day were the only runs that were explicitly considered unsafe by the deckhands due to the motions, wind conditions, and tension on the cables.

4.4.4 General remarks

- The position under deck felt safer than above deck due to being more sheltered from environmental conditions. However, participants felt higher situation awareness above deck because you can see more of your environment. Participants seemed to have a preference for having a team both above and below deck, rather than exclusively executing the operation from one specific position.

- The participants mentioned that they feel that the space between the messenger line and electricity cable should be increased. Furthermore, they mentioned that the line for the electricity cable should be longer than the pick-up line for the hawser.

4.4.5 Conclusions and Recommendations

The following conclusions summarise the deck operation findings of the present project:

- The participants were generally positive about the E-tower operation from the deck perspective. The participants felt generally safe during most conditions that they experienced and felt that the operational procedure that was shown to them made logical sense.
- The following attention points should be taken into account:
    - **Clear communication is essential:** Ambiguity in radio communication about the approach plan reduced safety and efficiency; this was highlighted as a risk by participants.
    - **Task allocation for HEHW/CEHW lowering should be further discussed:** Whether lowering should be done on deck or from the bridge requires clearer definition.
    - **Connection phase is the most critical moment:** The vessel must maintain a stable position for 5–6 minutes; poor coordination or sudden forces pose a potential safety risk.
    - **Strict protocols and supervision are required:** Clear procedures and active supervision during line connection are crucial to ensure deckhand safety.

5 CONCLUSIONS AND RECOMMENDATIONS

To evaluate the feasibility of performing charging operations at the North sea for an e-SOV at an e-Tower under design conditions, real-time manoeuvring simulations were carried out. Arrival, residence and departure scenarios were simulated at different environmental conditions. Evaluations were performed both in terms of vessel manoeuvring capabilities, and human safety and comfort for involved bridge and deck operation. Based on the observations and results of the simulations, the following conclusions and recommendations are made:

- Following the simulated cases, the available thruster power proved sufficient to control the vessel and conduct the manoeuvres safely in the typical north sea environment: 12.9 m/s wind speed, 2.5 m combined (sea + swell) wave height, covering roughly 80% of annual weather conditions in the data source location.

- In case of more extreme conditions (wind speed 20 m/s and 3.5 m total sea height; covering roughly 90% of annual weather), the vessel remained controllable with some challenges. Prolonged manned operation on open deck at such sea states and wind conditions are not recommended. However, the final judgement regarding the operational limits always rely on the captain and the crew.

- In general, the recommendation is always to bring in the vessel with a heading that is in equilibrium with the environment and request a tower boom angle accordingly. Once connected to the hawser, the preference would be to weathervane without any back thrust. If necessary, some power may be applied to reduce fish-tailing or approach towards the tower. However, preference would be to keep the back thrust very limited.

- The design for the hawser line seemed sufficient following the study. However, a dynamic mooring analysis is recommended to decide on the final hawser length and operational load.

- It is recommended to use a docking device during the operation with a clear indication of the distance to the e-Tower and tower boom heading. It is also recommended to install a camera at the bow and mooring deck of the vessel to monitor the hawser condition (e.g. to see if the hawser is connected, if it is in-slack or under tension). Also a load cell should be considered for monitoring the load.

- Hawser based operations are notably different when compared to a DP based system. Considering that most pilots/captains use DP onboard service vessels, it is recommended to familiarize and train the crew of the e-SOV with hawser operations. This includes handling the vessel in various situations, especially changing environmental conditions or extreme weather conditions. It is recommended to start operations at milder conditions to gain experience and confirm results from the simulations in practice.

- With partial loss of propulsion, the vessel still manged to safely move away from nearby assets in mean weather of the study location. In case of total loss of power while not connected to the hawser, the vessel may drift towards nearby wind turbines. Anchoring may be necessary in such case. However, this remains a very unlikely scenario for a vessel with DP2 and above.

Some general recommendations regarding the operation:

- It is recommended to define the approach speed and include them in the operational procedures of the terminal. Slow approach is always appreciated as it increases safety and more controllability. Thus, a distance based speed chart should help notably in standardizing operations with sufficient safety margins.

- Considering the relatively long charging period (roughly 18 hours), it is recommended to have some sort of automated control system that can assist the captain/watch keeper (when needed) with distance and tension control for the hawser line.

- Considering the relatively short time frame between approach and connection, no significant environmental changes are expected, so focus can be on the operation itself. In the optimal position (equilibrium), the environment should not cause a transverse movement. Longitudinal movement can be compensated by the thrusters during manoeuvring and by the hawser when moored.

- Picking up the messenger is a critical part of the operation. In windy conditions, this will likely be a challenge. The wind will not always be from straight ahead. Thus,

    - The line should be well visible and hang vertically, with a bottom weight to reduce swinging with the wind (as used in simulations). The lines should also be well visible at night.

    - It is also likely that over the years of operation, the messenger line will break sometimes. There should be an emergency procedure or alternative option in these cases.

REFERENCES

[Ref 1.] Actimar, *Metocean Design Criteria at L7B offshore The Netherlands*, 2015/10/30

[Ref 2.] Nordforsk, *Assessment of ship performance at sea*, 1987

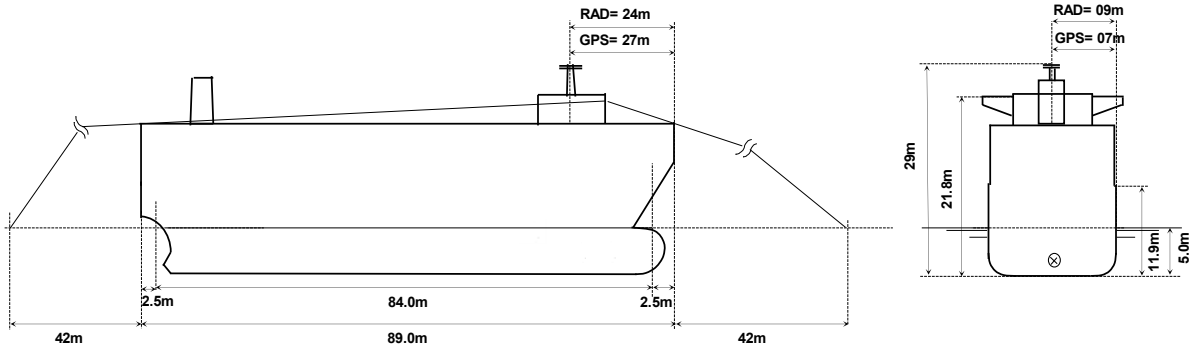
APPENDICES

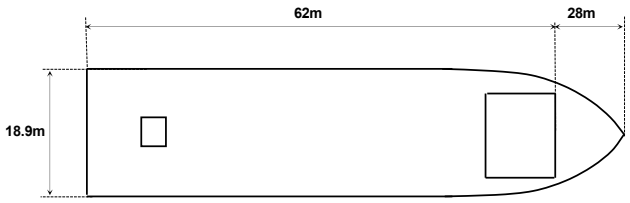
APPENDIX 1 PILOT CARDS

SHIP'S PARTICULARS

Length oa:	89.0	m	Lpp:	84.0	m	Anchor chain:	Port :	11	shackles
Breadth oa:	18.9	m	B moulded:	18.9	m		Stern:	n/a	shackles

Starboard: 11 shackles
(1 shackle = 27.5 m = 15 fathoms)





Manoeuvring engine order	RPM		Speed (kn) for indicated draught:
Full ahead at sea	250	-	12.9
Full ahead harbour	224	-	11.6
Half ahead	168	-	8.8
Slow ahead	119	-	6.3
Dead slow ahead	50	-	2.6
Stop	0	-	0.0
Dead slow astern	-50	-	
Slow astern	-119	-	
Half astern	-168	-	
Full astern	-224	-	

Type of engine:	Electric	
Maximum power :	2x400	kN
	#VALUE!	HP
Amount of propellers/rudders	1	
Rotation direction propeller	Inward over top	
Time limit astern :	0	min
Full ahead to astern :	0	sec.
Max. No. of consecutive starts:	7	times
Minimum RPM :	50	rpm

STEERING PARTICULARS

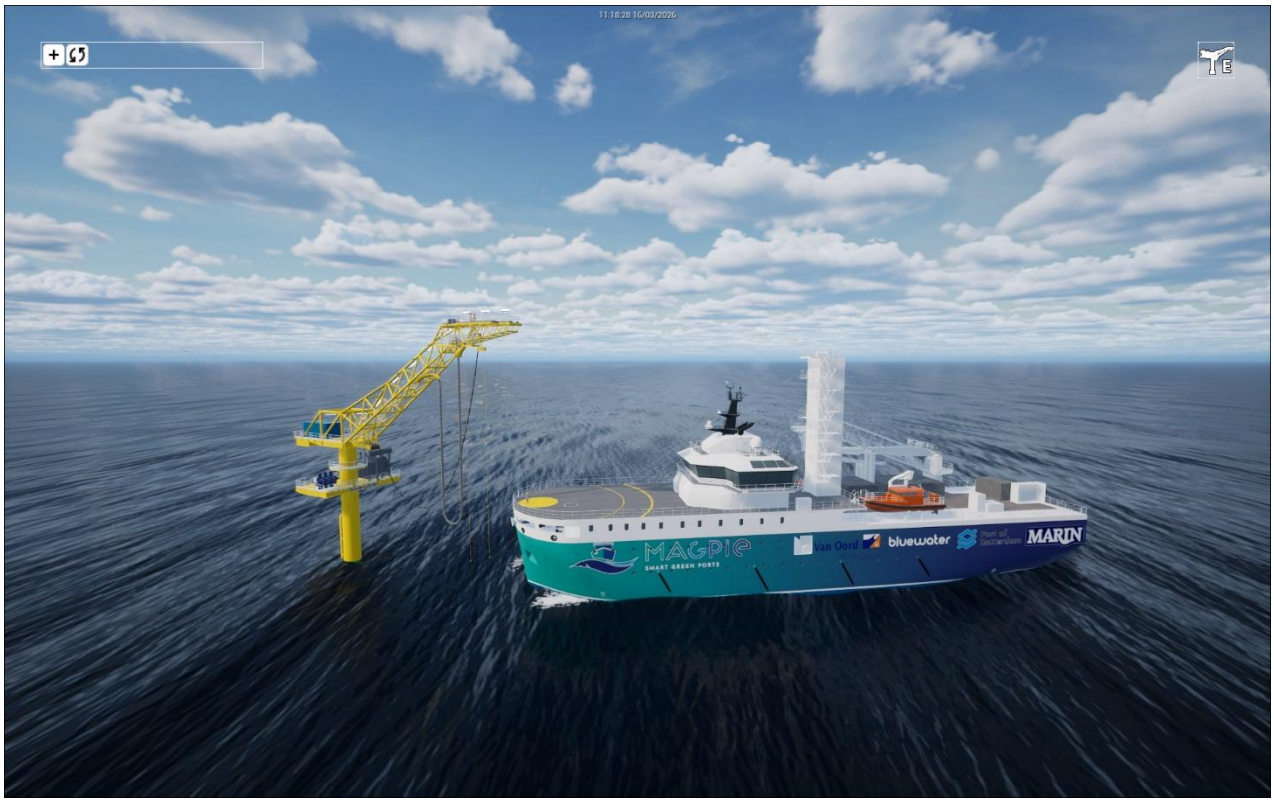
Type of rudder :	Azimuthing thrusters					Maximum angle :	180.0	deg		
Rudder angle for neutral effect :	0	deg				Hard-over to hard-over :	24.0	sec.		
Thruster bow :	2x150	kN	=	-	HP	Thruster stern:	0	kW	=	0 HP
							0	kW	=	0 HP

CHECKED IF ABOARD AND READY

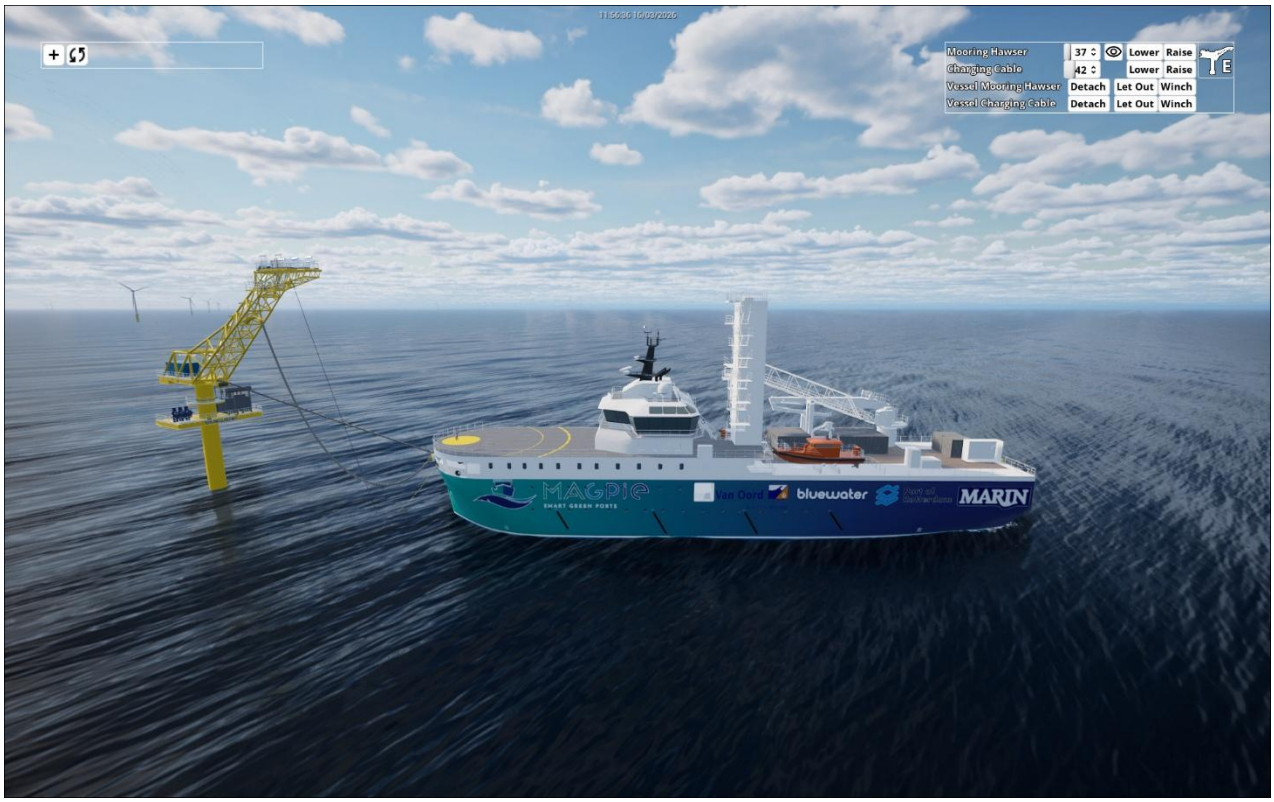
Anchors	x		Engine telegraphs	x		Compass system	x	
Whistle	x		Steering gear	x		Constant gyro error +/-	0	deg
Radar 3 cm	x	10 cm x	Number of power			VHF	x	
ARPA	x		units operating	2		Electronic position		
Speed log	Doppler:	yes	Indicators:			Fixing system	x	
Water speed	x		Rudder	x		Type	GPS	
Ground speed	x		Rpm/pitch	x				
Dual-axis	x		Rate of turn	x				

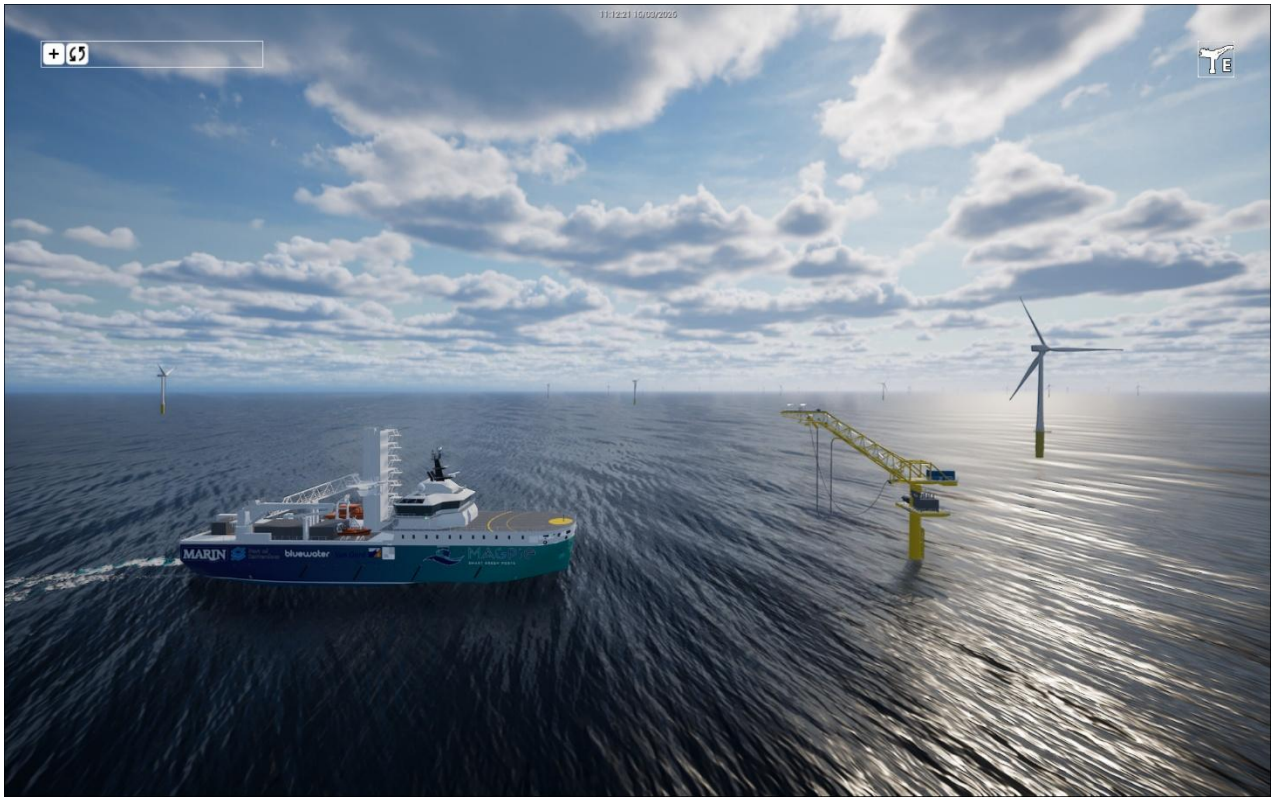
Maritime Research Institute Netherlands, P.O. box 28, 6700 AA, Wageningen, The Netherlands
Telephone: +31 317 479911, Telefax: +31 317 479999

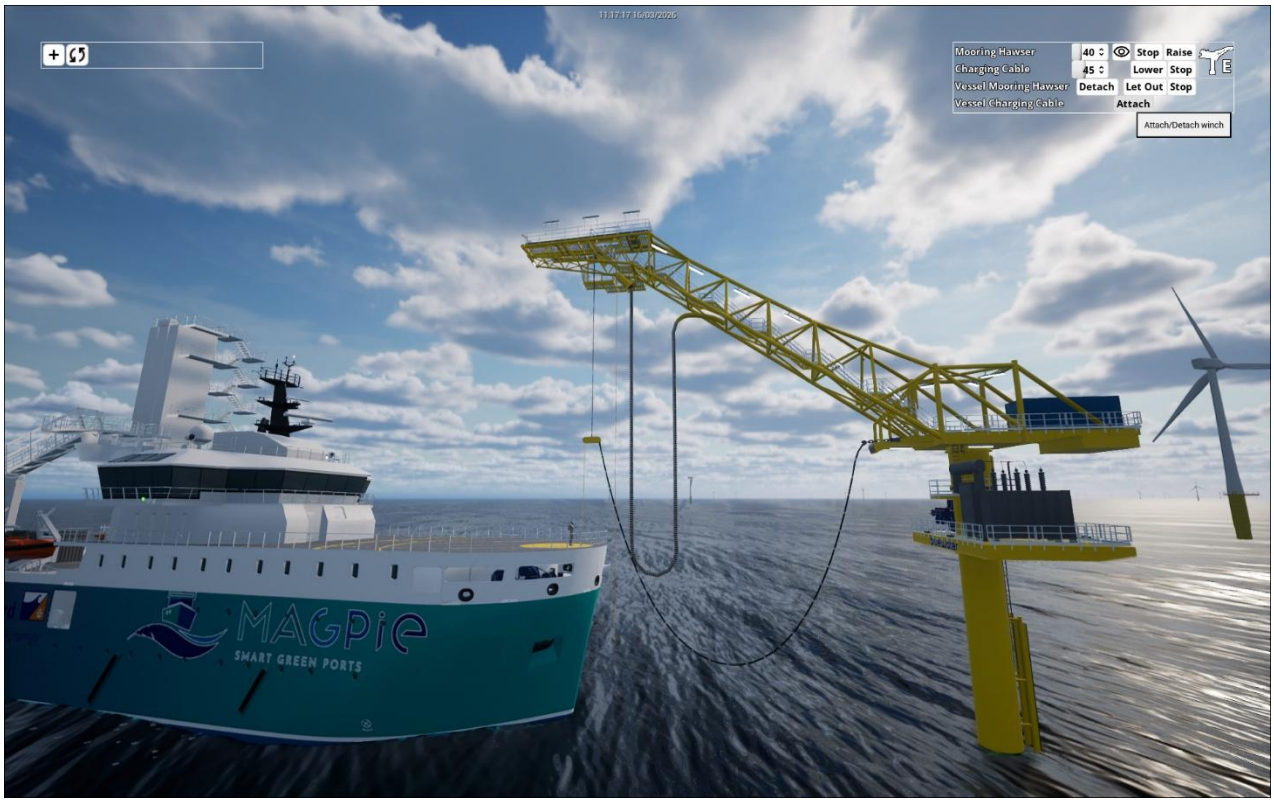
APPENDIX 2 VISUAL IMPRESSIONS FROM SIMULATIONS





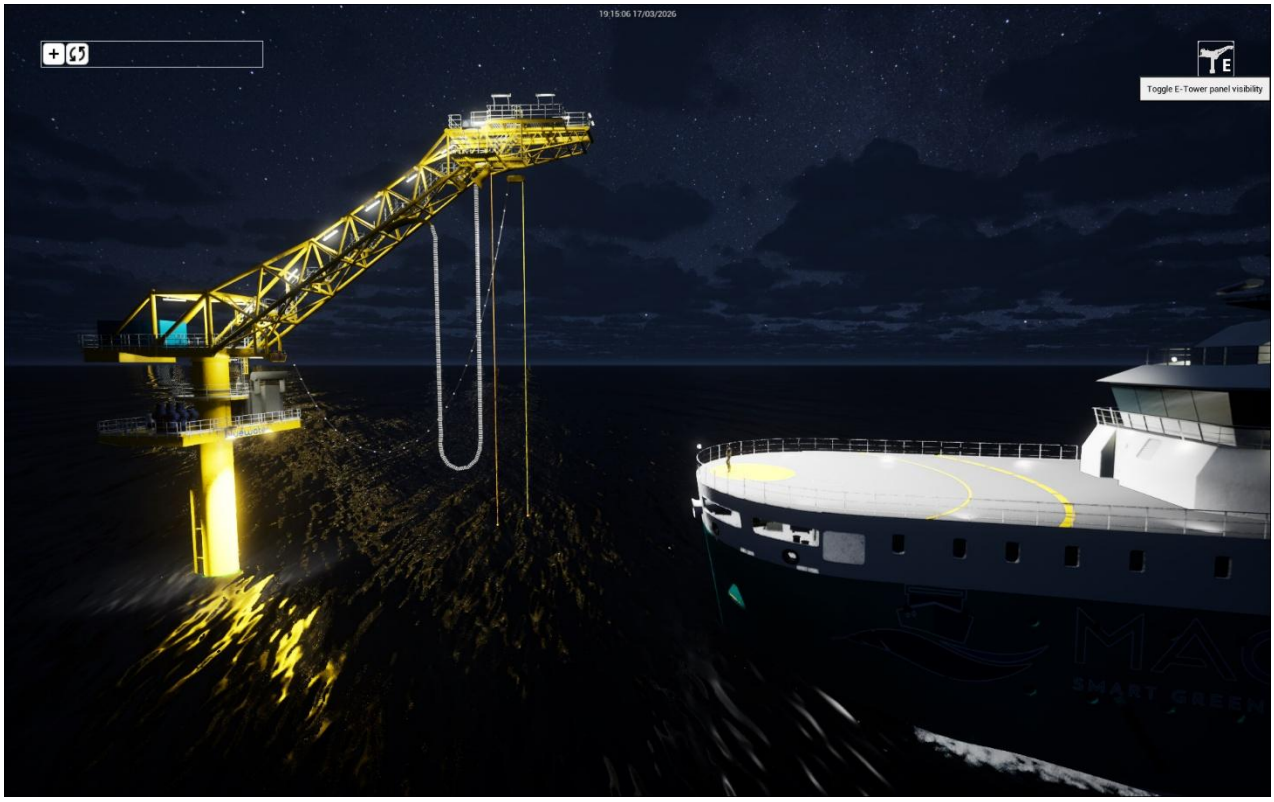

Mooring Hawser
Charging Cable
Vessel Mooring Hawser
Vessel Charging Cable
Lower
Raise
Detach
Let Out
Winch
MAGPIE
bluewater
MARIN

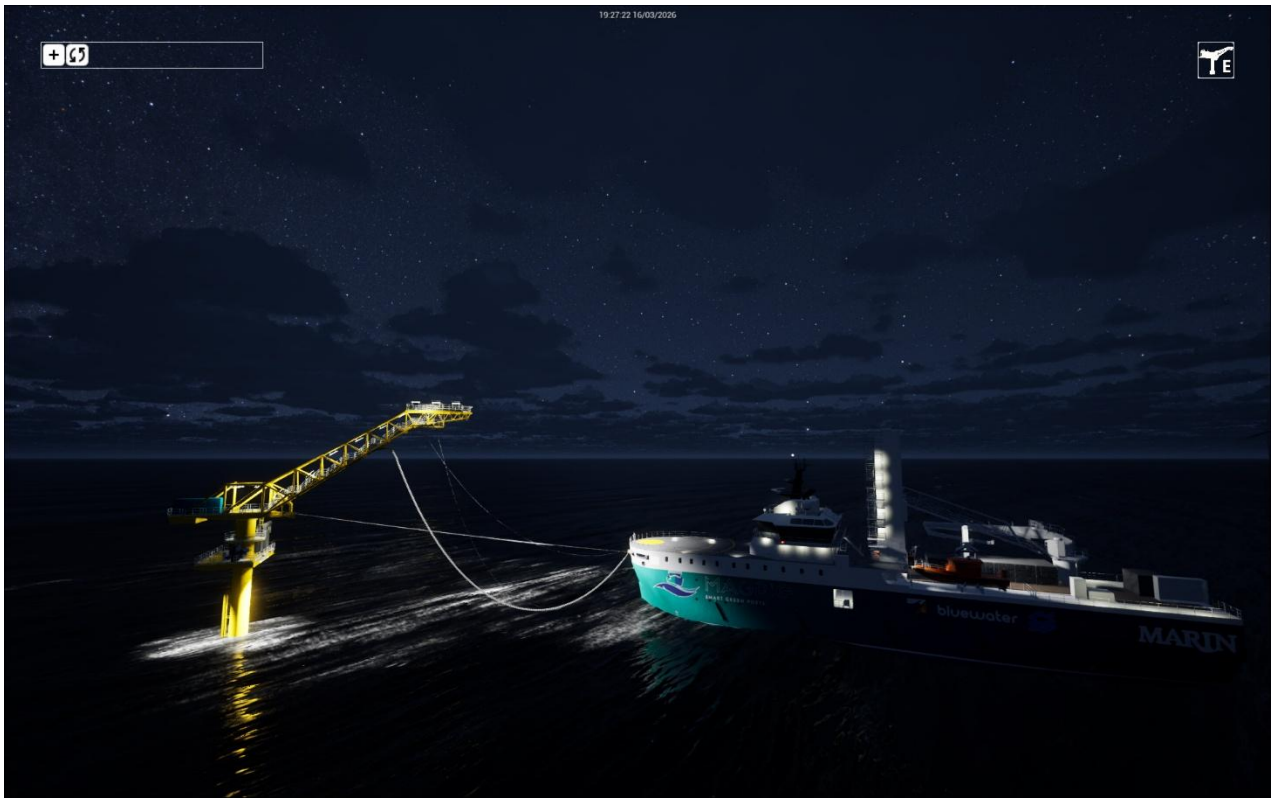

MARIN
bluewater
MAGPIE

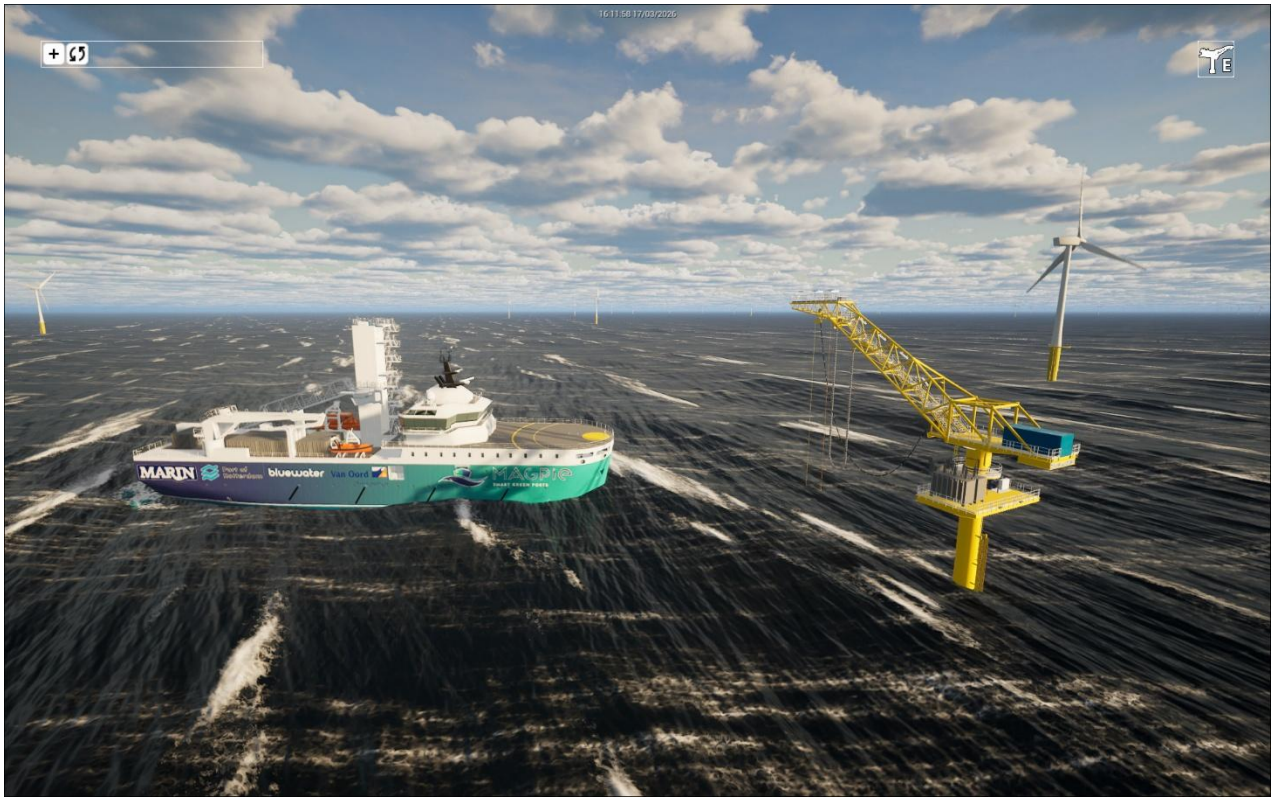

Mooring Hawser
Charging Cable
Vessel Mooring Hawser
Vessel Charging Cable
Stop
Raise
Lower
Stop
Detach
Let Out
Stop
Attach
Attach/Detach winch
MAGPIE
SMART GREEN PORTS

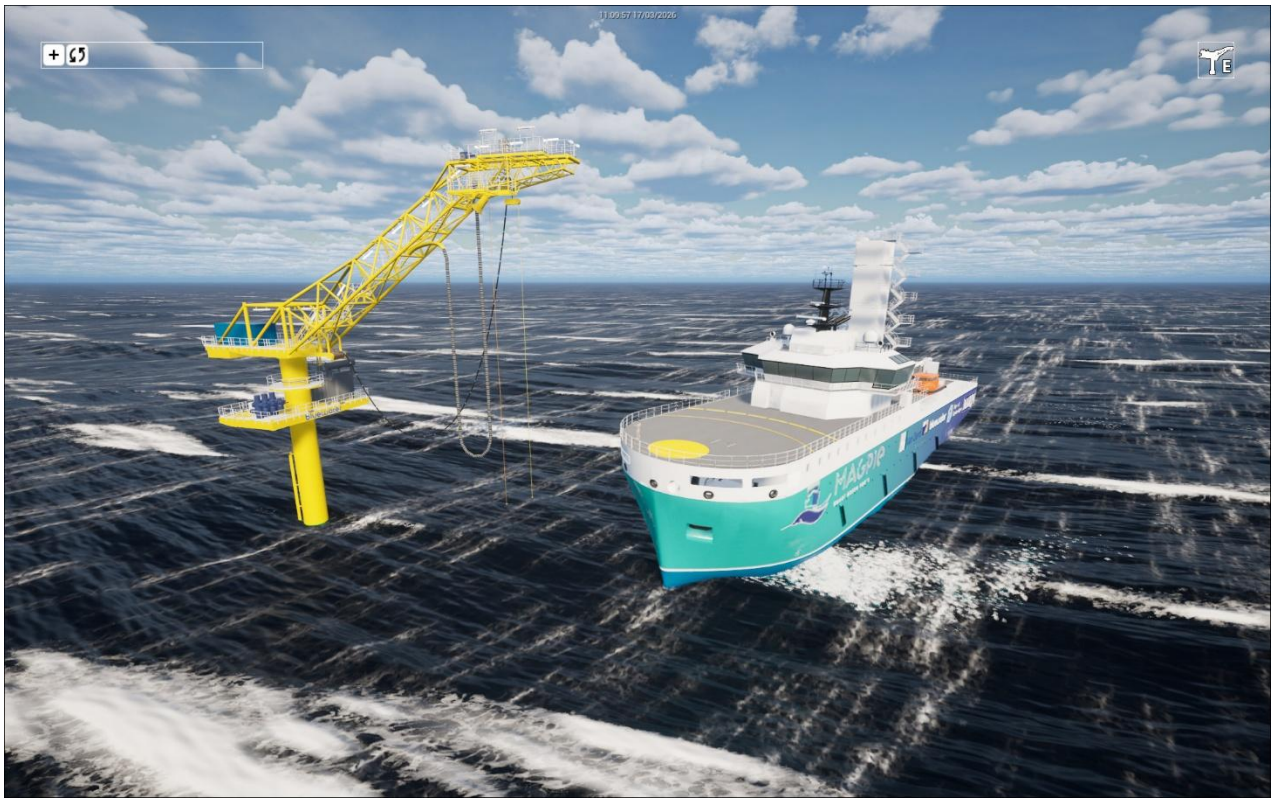

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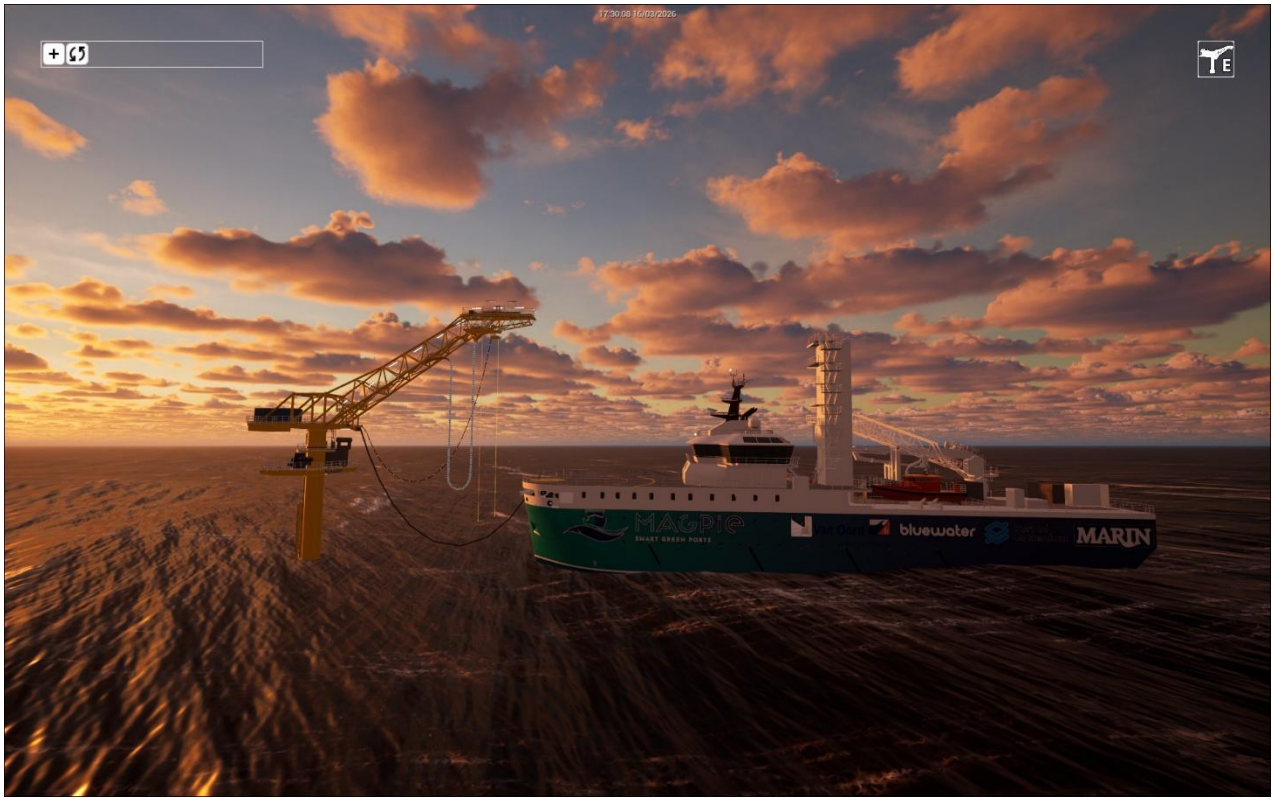

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Toggle E-Tower panel visibility

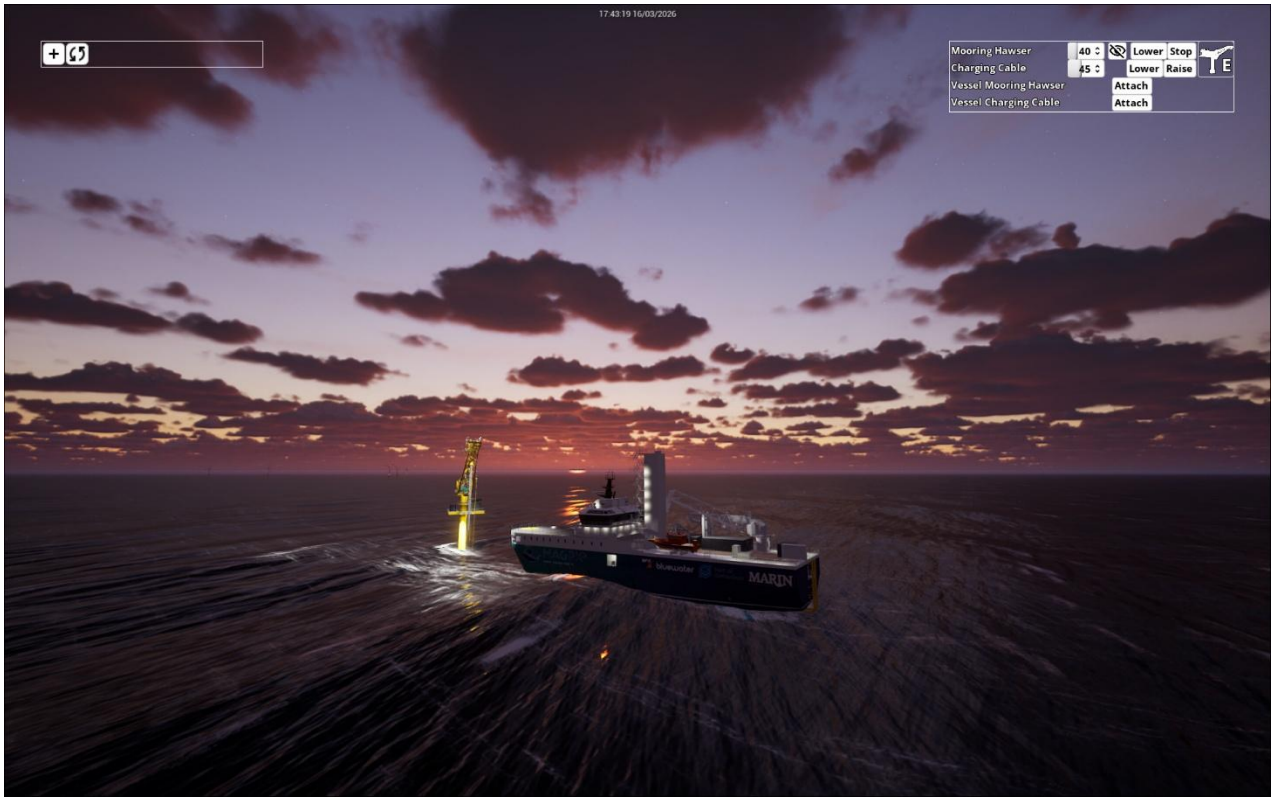

19:27:22 16/03/2026
bluewater
MARIN

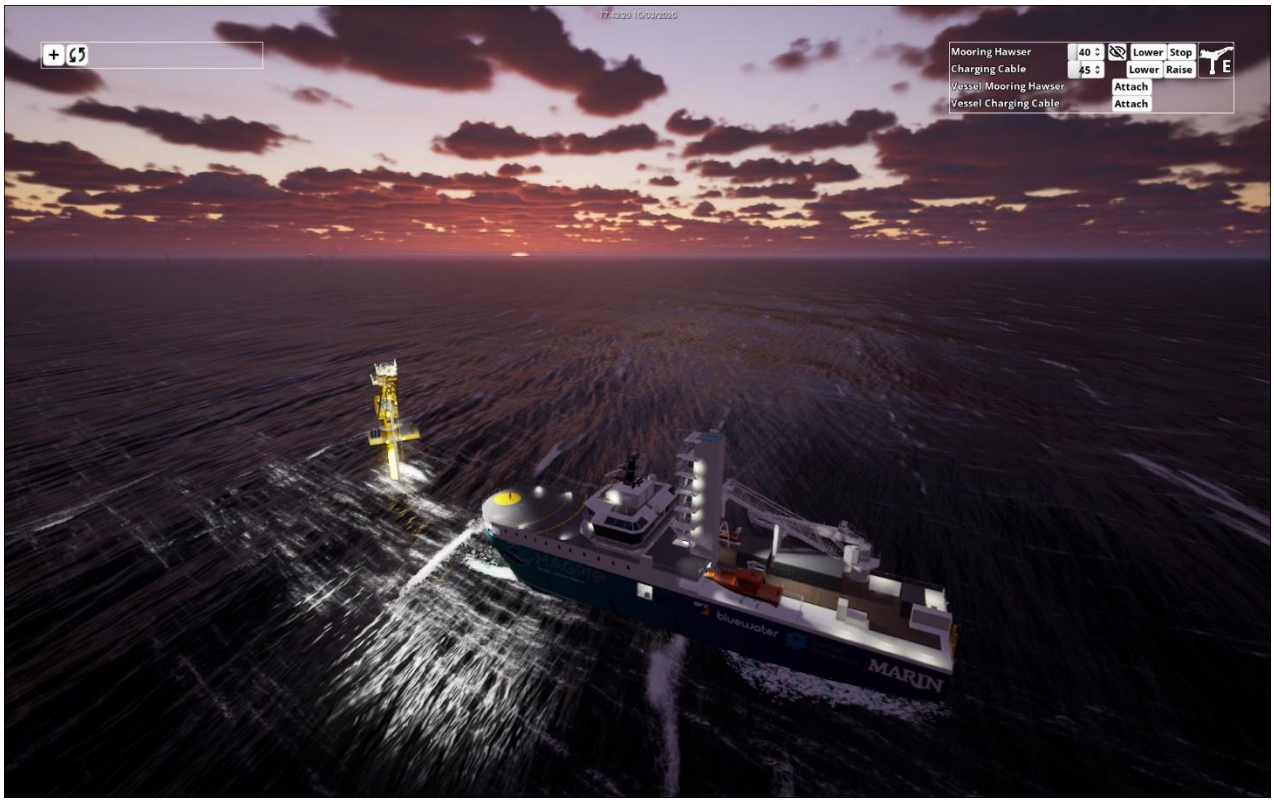

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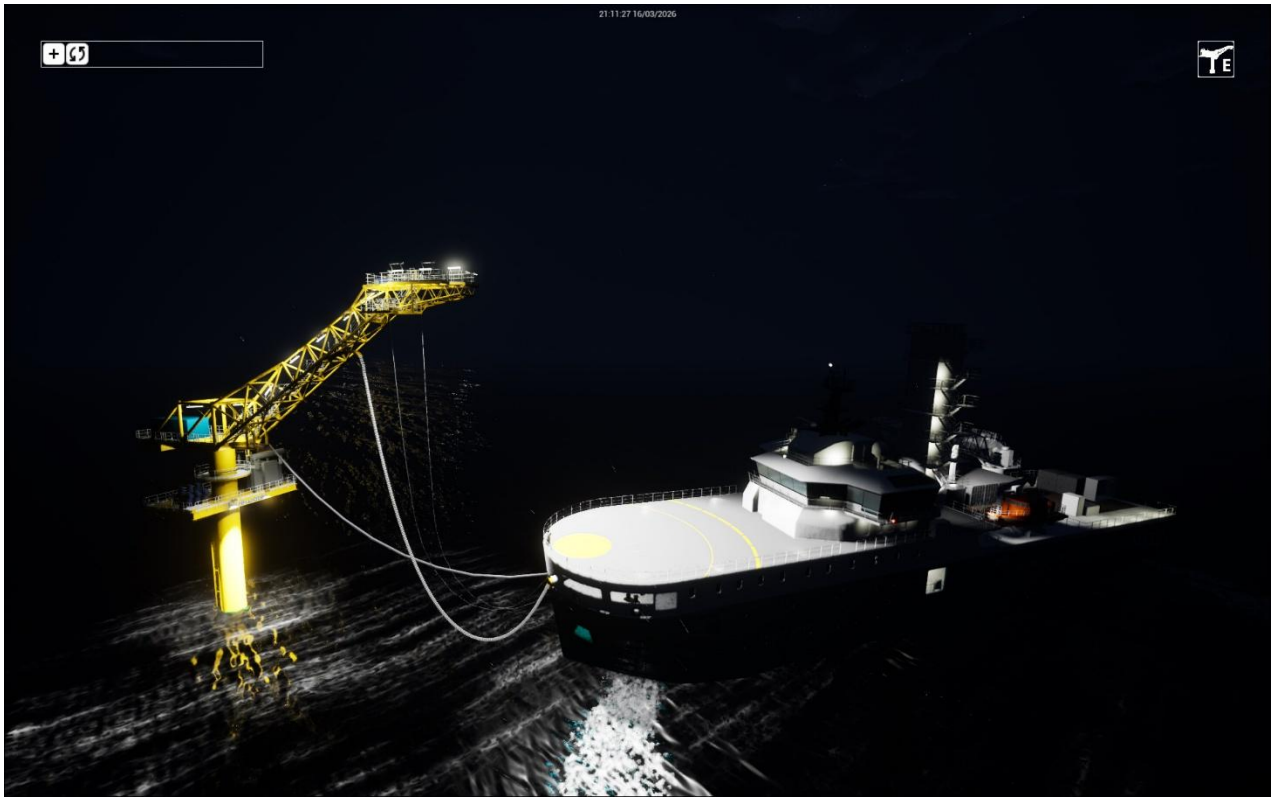

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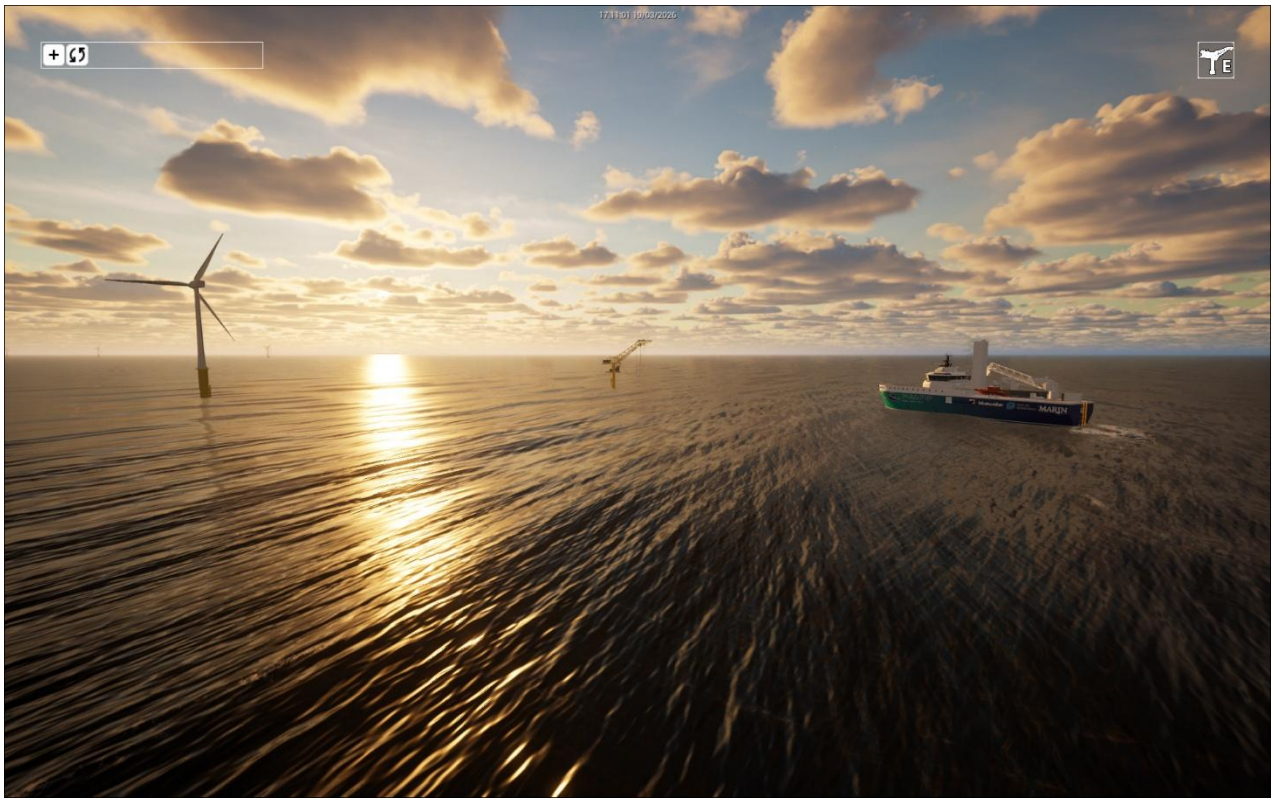

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bluewater
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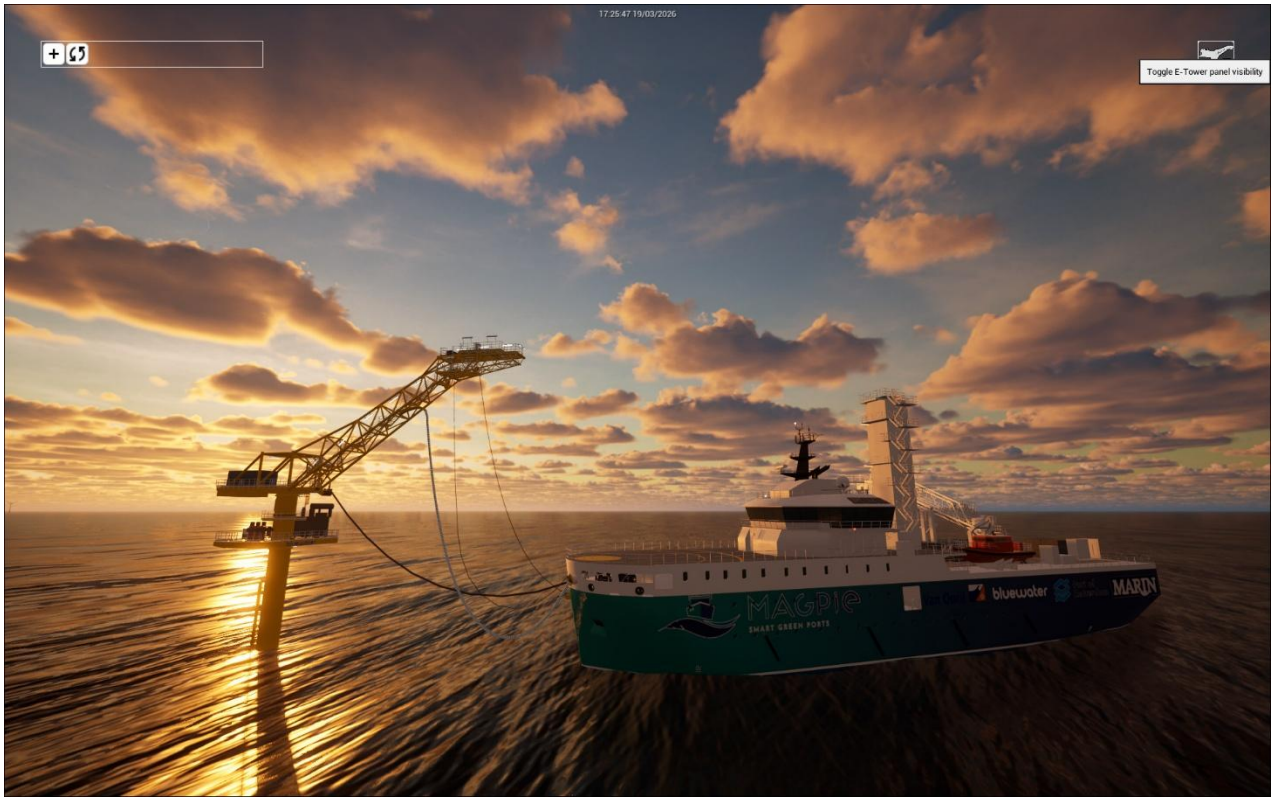



17:43:19 16/03/2026
Mooring Hawser
Charging Cable
Vessel Mooring Hawser
Vessel Charging Cable
40
45
Lower
Stop
Lower
Raise
Attach
Attach

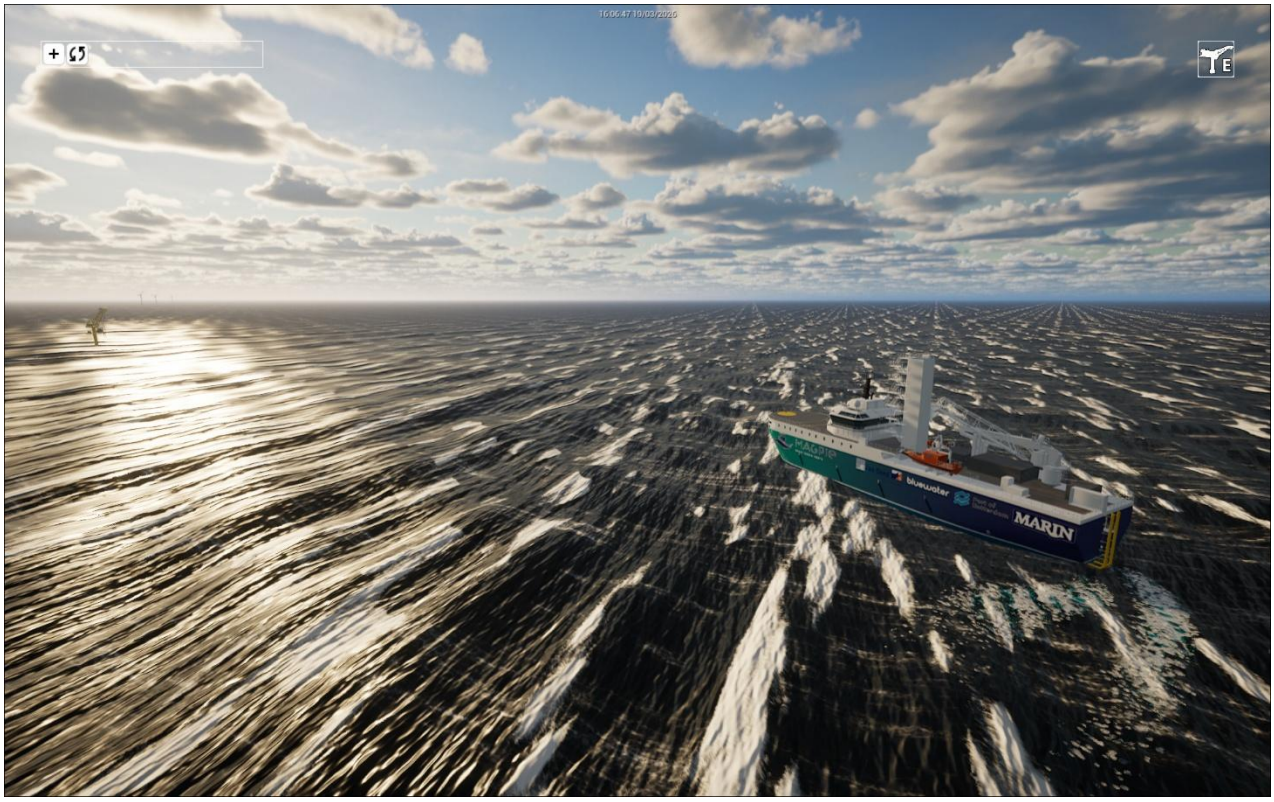

Mooring Hawser
Charging Cable
Vessel Mooring Hawser
Vessel Charging Cable
40
45
Lower
Stop
Lower
Raise
Attach
Attach
bluewater
MARIN


21:11:27 16/03/2026




17:25:47 19/03/2026
Toggle E-Tower panel visibility
MAGPIE
SMART GREEN PORTS
bluewater
MARIN


Mooring Hawser
Charging Cable
Vessel Mooring Hawser
Vessel Charging Cable
Lower
Stop
Lower
Stop
Attach
Attach
MAGPIE
bluewater


MARIN
bluewater

APPENDIX 3 TRACK AND DATA PLOTS

APPENDIX 4 BACKGROUND QUESTIONNAIRE

1. How many years of offshore experience do you have? **(open question)**
2. Have you ever encountered conditions during the operation that made it difficult or impossible to complete your tasks on deck? **(yes/no)**
3. Have your colleagues ever encountered conditions during the operation that made it difficult or impossible to complete their tasks on deck? **(yes/no)**
4. Which tasks were most challenging to complete under these conditions? **(open question)**
5. Which factors played a role? Multiple answers can be given. **(strong motions of the vessel/high wind speed/poor visibility/sea sickness/green water/other)**
6. Can you elaborate on one of your or your colleague's experiences in more detail? (e.g. what was the wave height, how was the weather, etc.) **(open question)**

M A R I N
P.O. Box 28

6700 AA Wageningen
The Netherlands

T +31 317 49 39 11
E info@marin.nl

I www.marin.nl