"CHANNELING THE GREEN DEAL FOR VENICE"
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CEF Connecting Europe Facility

# NAVIGATION SIMULATIONS

# Under-keel Clearance Capacity Assessment using NCOS ONLINE

| Activity | Phase 2 |
|---|---|
| **Task** | Under-keel Clearance Capacity Assessment using NCOS ONLINE |
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# 1 CONTENT

The final goal of the comprehensive set of undergoing activities is to quantify the impact along the Malamocco – Marghera Channel and surrounding areas induced by vessel transits in the Channel, to identify possible solutions aimed at minimizing the erosion processes that are now affecting the tidal flats surrounding the Channel, thus achieving sustainable navigation conditions.
To match this ambitious goal, following Public Tender procedures, the Contract was awarded by Port of Venice to a Consortium led by DHI S.r.l. and formed by DHI A/S, Force Technology, HS Marine S.r.l., Cetena S.p.A. and Around Water.

The present document presents an assessment of the operability of the MMC related to vessel underkeel clearance for selected designed vessels under one-year of meteomarine conditions (year 2020). The operability was calculated by using DHI's physics based Nonlinear Channel Optimization Simulator NCOS ONLINE software.

With reference to the "*Capitolato Tecnico*" the present document forms the first part of the following deliverables:

9. *Relazione tecnica dei risultati delle simulazioni di navigazione realizzate mediante auto-pilota ("fast time simulations");*
12. *Elaborati grafici di sintesi per la rappresentazione dei risultati dei modelli di navigazione.*

# 2 EXECUTIVE SUMMARY

DHI has undertaken a numerical study on the operability of the Malamocco-Marghera Channel (MMC). The operability assessment was based on under-keel clearance factors for selected design vessels. The study was a contribution to a broader investigation, which also comprised fast-time and full-bridge mission navigation simulations by FORCE Technology.

The study was performed for three vessels; a bulk carrier, a container vessel and cruise ship, with large draughts (11.00 m) currently allowed transiting MMC under certain conditions cf. the Port Rules (Ordinanza). Conservative, but realistic, assumptions on loading conditions and wave response were made.

Prior to the study DHI modelled one (1) full year of representative meteomarine forcing conditions for the entire Venice lagoon and MMC including water levels, winds, currents, and waves. One representative year, i.e., 2020 was modelled.

The under-keel clearance study was conducted by using DHI's physics based Nonlinear Channel Optimisation Simulator (NCOS ONLINE) that simulated both inbound and outbound transits throughout the one-year hindcast. Simulations were performed for each of the three vessels, assuming two different loading conditions. Ten (10) scenarios were modelled in total. In each scenario, 17,500 transits were simulated approximately, as a new transit was initiated every half hour. The same vessel speed profile was applied for the three vessels. Speed was 10 knots between Malamocco and the bend in San Leonardo, then the speed was reduced to 6.5 knots and kept constant until arrival in the port as per present Port Rules.

Vessels transited the centreline of the channel with the prescribed speed profile. Wind induced heel was included, which in turn resulted into vertical motions of the vessel hull. Wind induced-vessel drift and channel bank-effects were not included in initial simulations.

For each simulated transit, the Under-keel Clearance (UKC) and the Manoeuvrability Margin (MM) parameters were calculated. The UKC parameter quantified the grounding risk. The MM parameter indicated the existence of safe conditions for manoeuvrability. Both metrics represented a vertical distance between the vessel keel and the channel bed, and they were calculated as the combined effect of waves (only for UKC), squat, and dynamic heel.

The operability of each simulated transit was assessed as in Table 1.

*Table 1 Operability transit criteria applied in the study.*

| Parameter | UKC (m) | MM (m) |
|---|---|---|
| Transit operable | > 0.50 m | > 0.60 m |
| Transit inoperable | < 0.50 m | < 0.60 m |

A safety UKC margin of 0.50 m was used; this means that a grounding was defined as the event in which the keel was at a distance less than 0.50 m from the channel bed, and *not* necessarily when the keel *touched* the bottom.

The full one-year operability screening for all simulated transits led to these main results:

- A total operability of approximately 9% was obtained for both the Bulk Carrier and the Container vessel, combining the results for inbound and outbound transits as well as minimum and maximum loading conditions. The total operability was defined as the number of operable transits relative to the total number of transits.
- All simulated transits with the cruise ship succeeded. This finding does not imply that no weather-related operational limits exist for cruise ships. In fact, manoeuvrability of cruises is troubled by wind-induced drift, which was not modelled in the present study.
- For inbound transits of the Bulk Carrier and the Container Vessel, the highest operability (50%) was found when voyages started between 1.5 and 1 hour before the high tide at Punta della Salute reference station. For outbound transits, the highest operability was 35% when leaving Marghera no earlier than 30 min before the high tide at Punta della Salute. Inbound and outbound transits starting at low tide in Punta della Salute were inoperable.

- No specific section of the channel restrained the operability. Most of the transit failures took place consistently along the bend in San Leonardo and along the North-South MMC alignment, where shallower depths are located.
- Operability had a strong dependency on the water level (Figure 1). In this regard, initiating a transit with a water level above approximately +0.50 mMSL (+0.82 mZMPS) at Punta della Salute ensured a safe UKC margin of minimum 0.50 m. This occurs 8% of the time.
- Wind conditions, through the induced heel, did not have a significant impact on the operability (Figure 1). However, strong winds are generally expected to worsen the vessel manoeuvrability conditions, hence the channel operability. Wind-induced drift can push vessels towards the shallower sides of the channel where grounding is likely to happen. As mentioned, this circumstance was not modelled and, consequently, it did not affect the presented results.

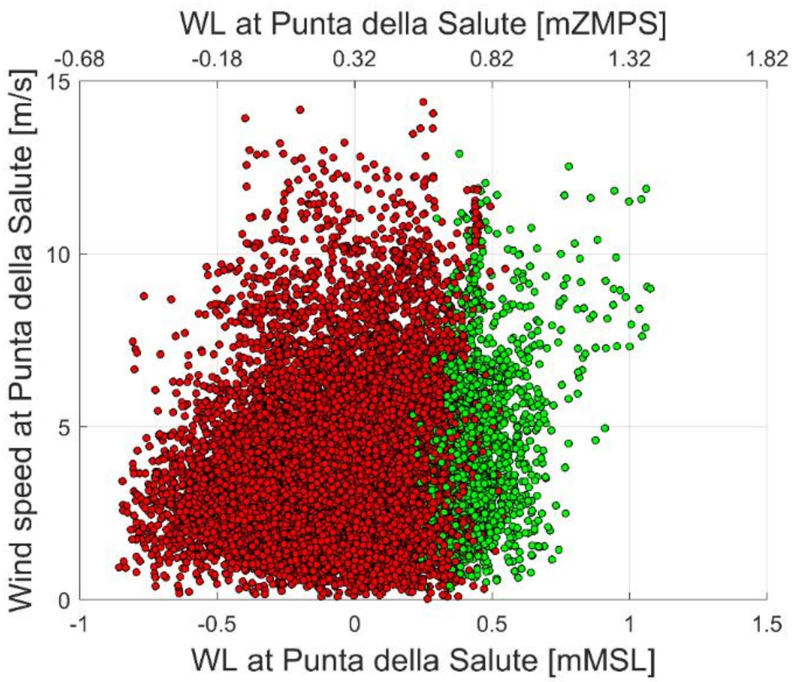



*Figure 1 Combination of water level and wind speed at Punta della Salute at the departure times of the simulated transits. Colors indicate the outcome of the operability assessment for each transit, i.e., red for inoperable and green for operable transit.*

# 3 THE MALAMOCCO-MARGHERA CHANNEL

Malamocco is one of the three mouths of the Venice lagoon, and it accommodates the entry of cargo ships (Figure 2). Through a channel (red in Figure 2), ships reach the commercial and industrial facilities of Marghera port (orange area). The Malamocco-Marghera Channel, hereafter MMC, is 9 nm long approximately with depth varying between 12.5 m and 28 m Chart Datum. The channel follows two main alignments, i.e., ESE-WNW before the bend near San Leonardo and N-S after the bend.

The overview map in Figure 2 shows some representative locations along MMC that are used in this report to present and discuss results, namely *Malamocco*, *San Leonardo*, *Motte di Volpego*, *Fusina*, and *Marghera*.

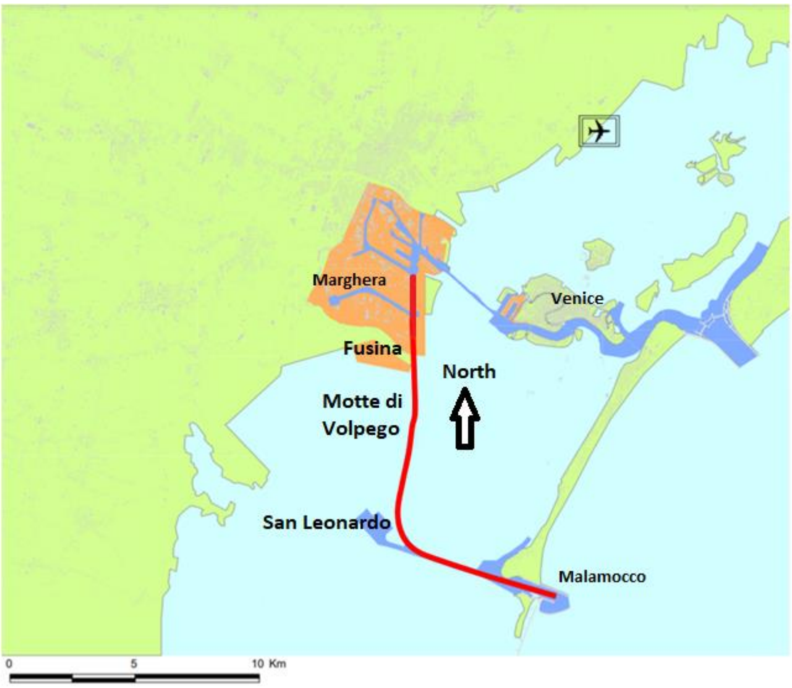



*Figure 2 Alignment of the Malamocco-Marghera Channel located in lagoon of Venice, Italy. Image ©Port of Venice.*

### 3.1.1 Bathymetry

The bathymetry of the entire lagoon was built and consolidated upon the different sources listed in Table 9 of [1]. In the present study, only the bathymetric data along MMC was used (dataset no. 3 in Table 9 of [1]). Data was provided by **Port of Venice** with horizontal coordinates in WGS1984 and vertical datum in IGM42 (Chart Datum, CD). The horizontal resolution was 3.0 m approximately. Data was obtained from several surveys carried out between 2017 and 2021, including the survey conducted after the dredging operations in 2021.

Figure 3 displays an overview of the bathymetry in the study area. Figure 4 shows a depth profile along the centreline of the MMC. The water depth is around 14 mIGM42 at Malamocco. Deeper depths down to 28 mIGM42 follow initially. Before the bend towards Marghera, water depths decrease to 14 mIGM42. Along the bend and along the South-North leg of the channel, water depths keep decreasing to 12.5 mIGM42 approximately. Finally, depths increase down to 14 mIGM42 towards the swinging basin at the end of the channel. The channel width comprised between the 11.50 mIGM42-depth contour lines is around 200 m near Malamocco; it decreases to 100 m approximately along the bend at San Leonardo, and it decreases further to around 60 m along the N-S alignment towards Marghera.

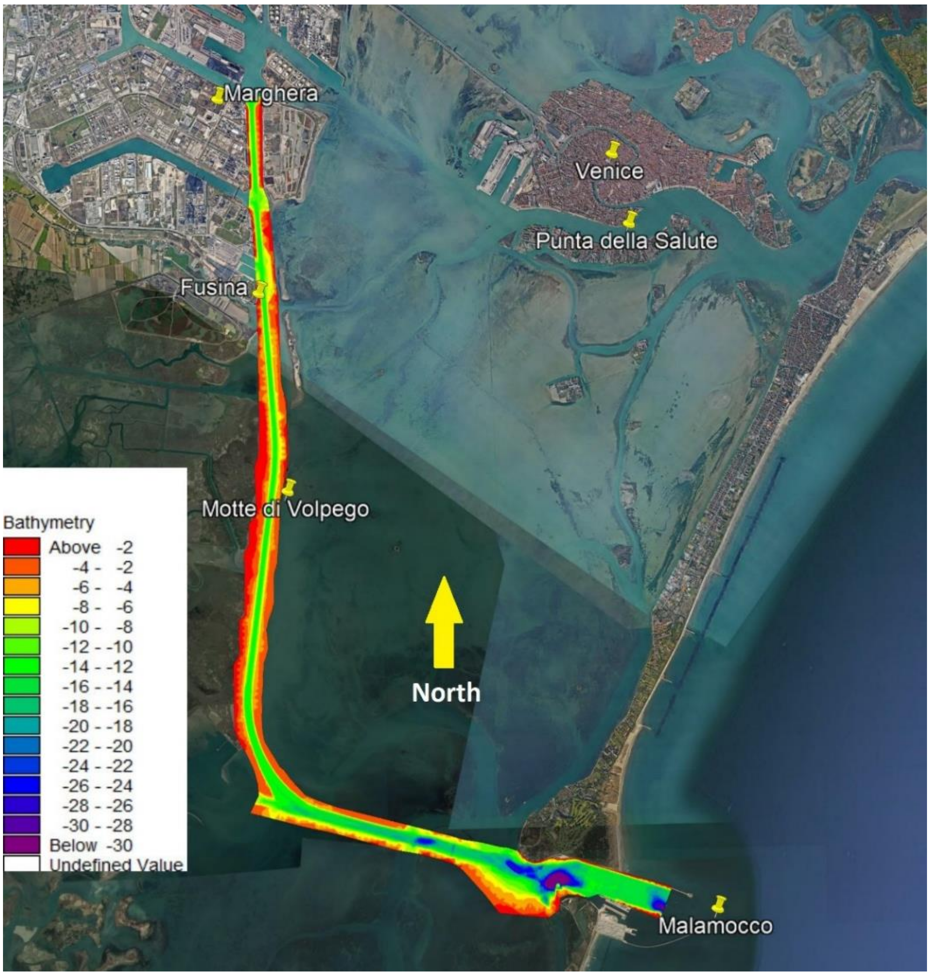



*Figure 3 Bathymetry (IGM42 datum) of the MMC. Satellite background from ©Google Earth.*

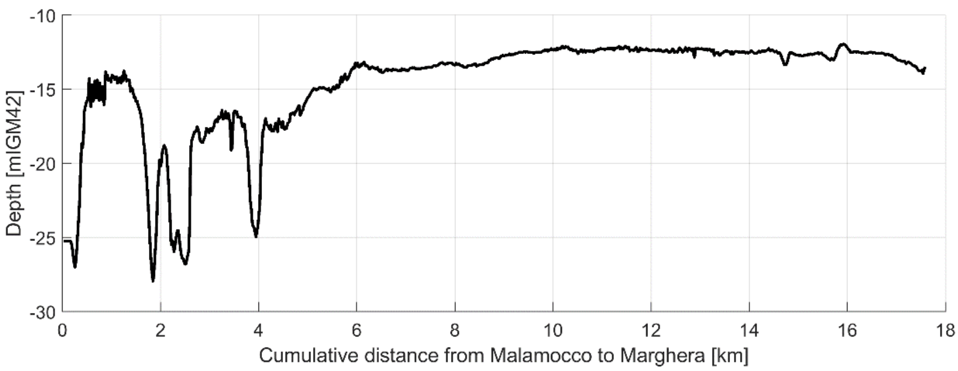



*Figure 4 Bathymetry profile along the centreline of the MMC.*

### 3.1.2 Relevant vertical datum conversions

Different vertical datums were used in the study:

- bathymetric data were received in IGM42
- the hydrodynamic simulations were performed with bathymetric input relative to Mean Sea Level (MSL)
- results are presented in the following with reference to ZMPS (Zero Mareografico di Punta della Salute), which is the vertical datum traditionally used by regulators and operators in the Venice lagoon for water level measurements.

The relation between the three datums is depicted in Figure 5, where it can be read that $MSL = IGM42 - 0.084\ m = ZMPS - 0.32\ m$

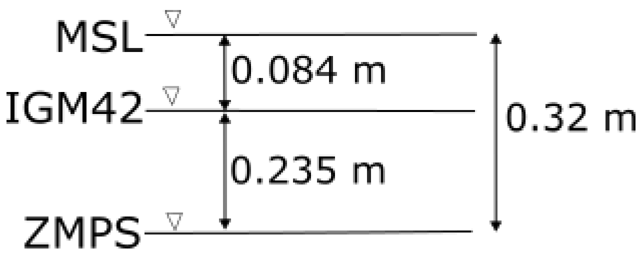



*Figure 5 Relation amongst the three relevant datums used in the study, i.e. MSL, IGM42, and ZMPS.*

### 3.1.3 Draft and water level operational limits for allowed transits

Current port operating rules [2] prescribe the maximum vessel draft for allowed transits along the MMC.

As reported in Table 2, the maximum draft depends on the vessel dimensions when the tidal water level (WL) is measured above MSL. When the WL is below MSL, the maximum allowed draft is found by subtracting the absolute value of the water level from the draft allowed with positive WL. As an example, if WL = -0.50 mMSL and the vessel has dimensions up to 230 x 33 m, the maximum allowed draft is 11.00 m.

*Table 2 Maximum vessel draft limits for navigation along the MMC (from [2]).*

| Max vessel dimensions LOAxB [m] | Draft [m] | |
|---|---|---|
| | With WL > 0 mMSL | With WL < 0 mMSL |
| 230 x 33 | 11.50 | Max draft with positive WL – abs(negative WL) |
| 270 x 37 | 11.30 | |
| 300 x 41 | 10.80 | |
| 335 x 45 | 10.50 | |

# 4 MODELLED METEOMARINE CONDITIONS ALONG THE MALAMOCCO-MARGHERA CHANNEL

Environmental conditions such as tidal water levels, currents, waves, and winds, are governing factors for the safe navigation conditions in the MMC. A comprehensive analysis of the meteomarine conditions was therefore undertaken prior the present study in [1]. In fact, the metocean forcings were modelled on the entire Venice lagoon over one (1) selected representative year. As explained in [1], the year 2020 was selected because:

- it exhibited “above-average” conditions, but not extreme metocean conditions
- observed data such as water levels and waves at the three lagoon mouths was sufficiently available. This data was used in [1] to generate model boundary conditions

With respect to the first motivation, it should be noted that the present study concerned the *existing* MMC. Therefore, the focus was not on extreme metocean conditions typically used for design.
As it will be shown in Section 6, thousands of transits (inbound and outbound) were simulated along the channel over the year 2020, therefore a single year was sufficient to obtain statistically confident estimates of the channel operability.

The following sections present the main outcome of the hindcast for year 2020 and relevant for the present study. The presented results are either instantaneous or statistical values from the metocean study, whereas the time- and space-changing modelled conditions were applied in the simulated transits along the channel. Results are shown at Malamocco and Fusina locations.

## 4.1 Tidal water levels

Figure 6 and Figure 7 display the tidal water levels for year 2020 at Malamocco and Fusina respectively. The tidal water levels varied mostly between -0.5 mZMPS and 1.0 mZMPS. From Figure 6, a period with higher water levels up to 1.5 mZMPS occurred in December at Malamocco. As discussed in [1], the M.O.S.E. system was modelled and assumed to be operating during that period, thus preventing the high-water levels from propagating into the lagoon and reaching e.g. Marghera.

The tidal variation is mostly semi-diurnal meaning that low water occurs approximately twice a day, with around 12 hours between the two low waters. As an example, a daily variation is depicted in Figure 8 at both Malamocco and Fusina. In the same figure, the tide at Punta della Salute is also shown, which followed the variation in Fusina very closely. It is observed a time shift of 70 minutes approximately between Malamocco and the other two locations inside the lagoon.

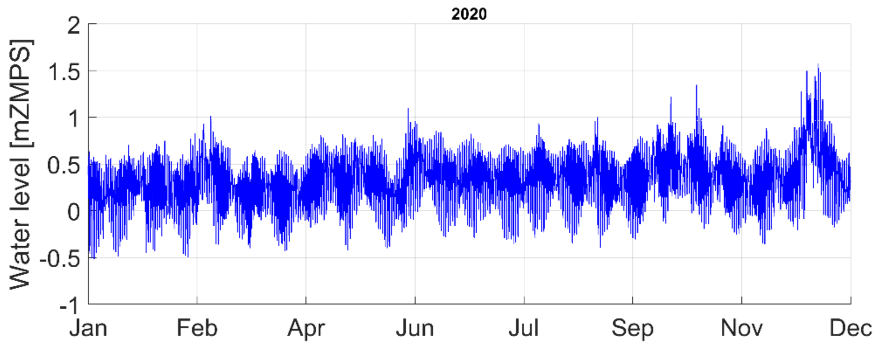



*Figure 6 Tidal water level at Malamocco during year 2020 (hindcast).*

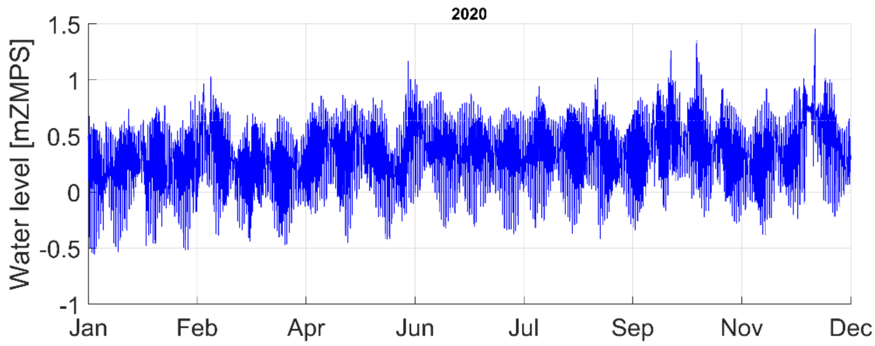



*Figure 7 Tidal water level at Fusina during year 2020 (hindcast).*

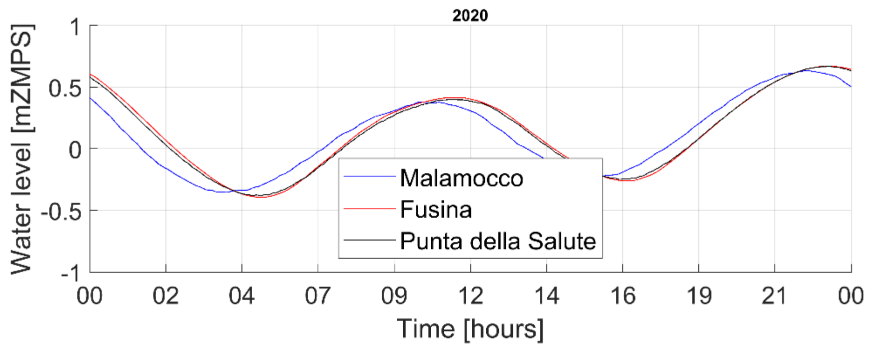



*Figure 8 Comparison between water level at Malamocco, at Fusina and at Punta della Salute (8 April 2020, hindcast).*

## 4.2 Wind

The directional distributions of the 10m wind speed at Malamocco and Fusina are shown in Figure 9 and Figure 10, respectively. The two distributions are slightly different because of the spatially and temporally varying input wind field applied in the metocean modelling (Section 5.1.3.1 of [1]). At both locations, it can be observed that wind directions (coming-from) were concentrated primarily in the N-E sector in 2020. Moreover, up to 5% of the winds came from the SE-S sector. The highest wind speeds were around 18 m/s at both locations.

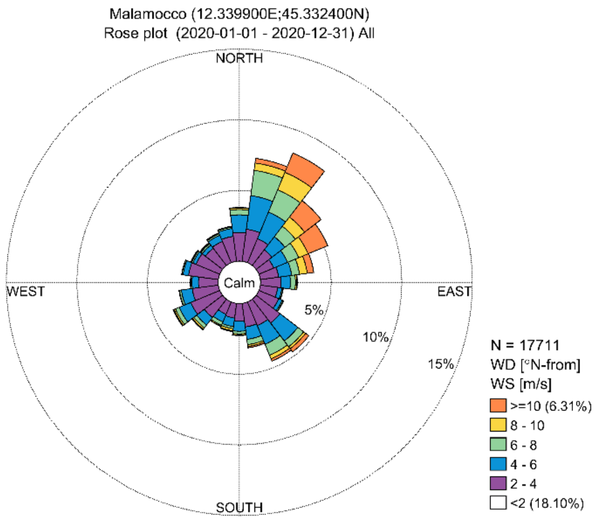



*Figure 9 Directional distribution of 10m wind speed during year 2020 at Malamocco (hindcast).*

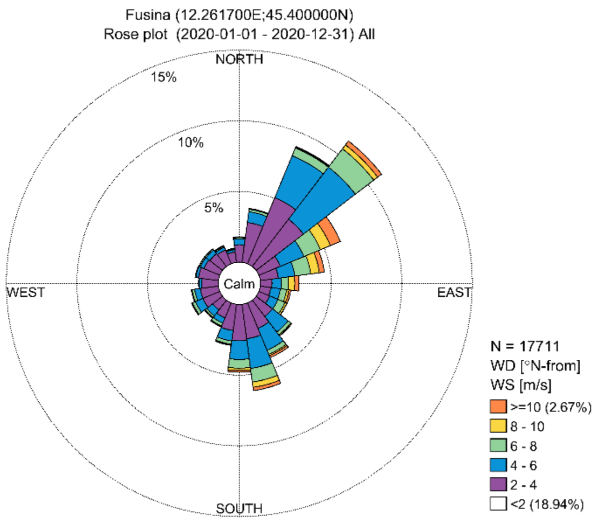



*Figure 10 Directional distribution of 10m wind speed during year 2020 at Fusina (hindcast).*

## 4.3 Currents

Figure 11 and Figure 12 show the directional distributions of current speeds (depth-averaged) during the year 2020 at Malamocco and Fusina, respectively. The two distributions are representative of the current conditions along the two main alignments of the MMC. Before the bend near San Leonardo (Figure 2), currents moved along the ESE-WNW directions; after the bend, currents moved along the N-S directions. The maximum speed at Malamocco was around 2 m/s (4 knots). The maximum speed at Fusina was around 0.7 m/s (1.4 knots). Looking at the distribution at Fusina, it is noted that north-going currents occurred more frequently than south-going currents in 2020.

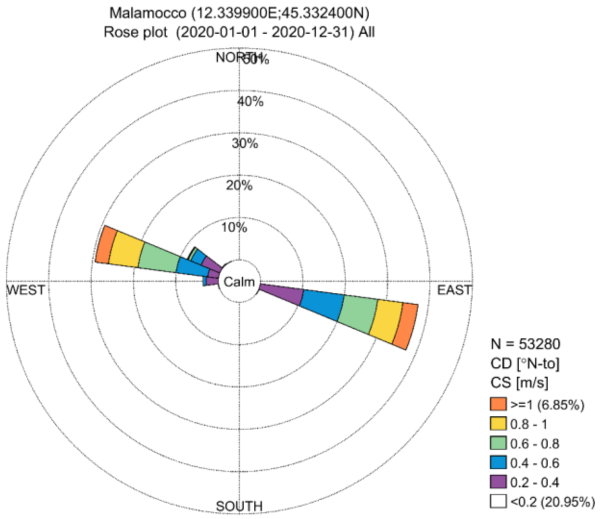



*Figure 11 Directional distribution of current speed during year 2020 at Malamocco (hindcast).*

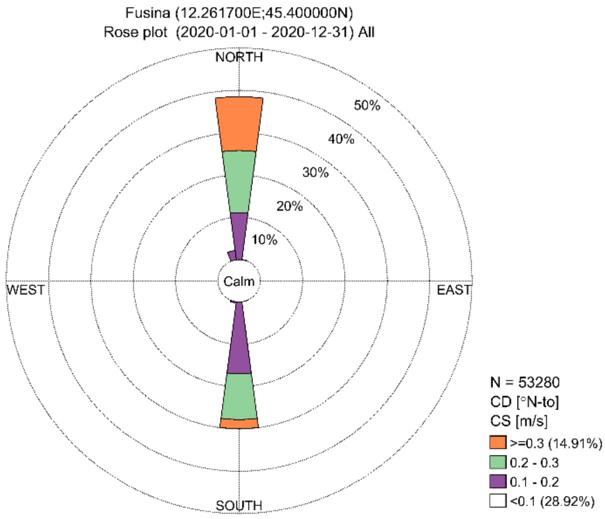



*Figure 12 Directional distribution of current speed during year 2020 at Fusina (hindcast).*

## 4.4 Waves

The directional distributions of significant wave heights, $H_{m0}$, and peak wave periods, $T_p$, during the year 2020 are plotted in Figure 13 and Figure 14 for Malamocco and Fusina, respectively. Waves entered the channel from ESE through Malamocco. Looking at the roses in Fusina, it can be recognized that, after the bend, waves were from either south or nearly north-east.

Figure 15 clearly shows that wave heights reduced considerably after the bend in San Leonardo. In the following, it will be shown that waves did not generally induce significant vessel motions along the channel, hence waves did not have a significant impact on the UKC-related channel operability.

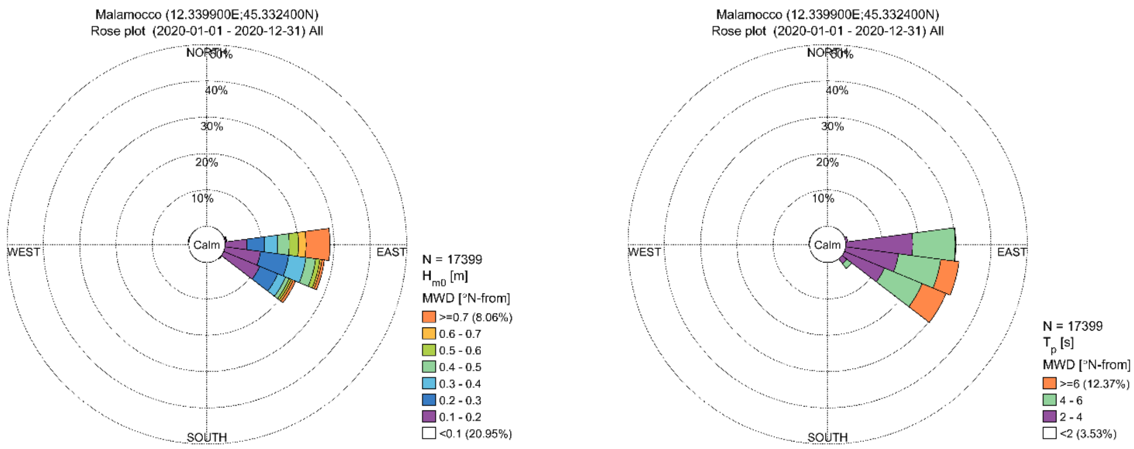



*Figure 13 Directional distribution of significant wave height, $H_{m0}$ (left), and peal wave period, $T_p$ (right) at Malamocco (hindcast).*

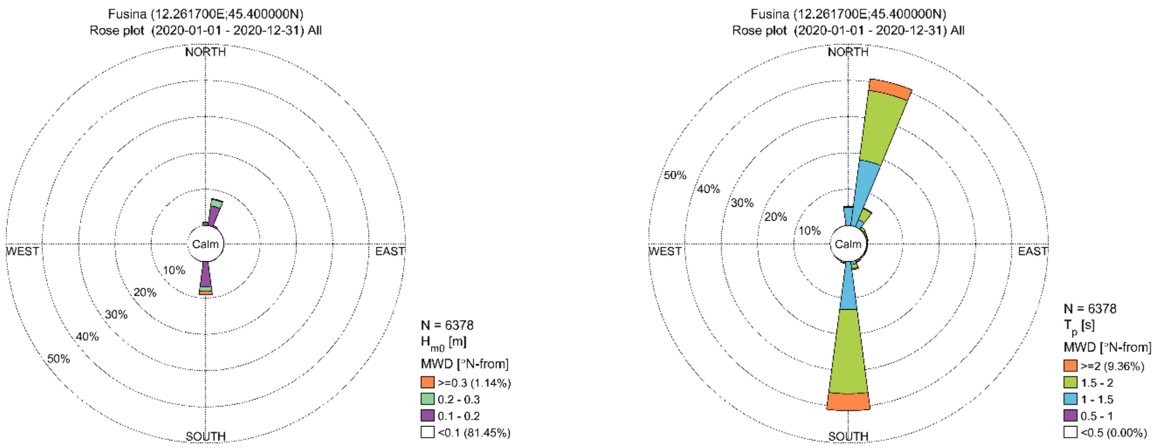



*Figure 14 Directional distribution of significant wave height, $H_{m0}$ (left), and peal wave period, $T_p$ (right) at Fusina (hindcast).*

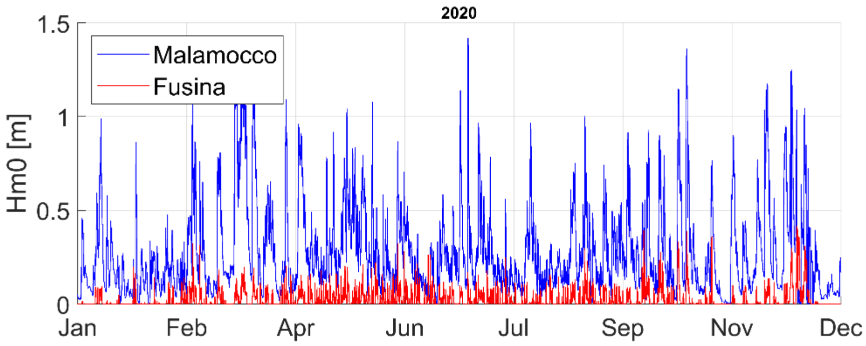



*Figure 15 Comparison between significant wave height, $H_{m0}$, at Malamocco and at Fusina during year 2020 (hindcast).*

# 5 VESSELS USED IN THE STUDY

Port of Venice advised the three vessels in Table 3 for the assessment of the MMC operability study. More details on the vessel particulars are given in Appendix A.

*Table 3 Length Overall, beam and draught of the three vessels used in the study.*

| Vessel | LOA [m] | Beam [m] | Draught [m] |
|---|---|---|---|
| Bulk carrier | 260 | 37 | 11.00 |
| Container ship | 220 | 32.2 | 11.00 |
| Cruise ship | 293 | 32.2 | 7.85 |

These three vessels, with associated draught values, represent the largest vessels currently accommodated in the MMC. The selection was thus in accordance with the scope of the present study that was to investigate the operability of the existing MMC.

Numerical ship models were developed and provided by FORCE for each of the three vessels to produce NCOS ONLINE modelling input such as Response Amplitude Operators (RAOs) and windage areas. The numerical ship models of the three vessels were created based on:

- Hull geometry based on grids of similar size vessels in same class, scaled to the target ships
- High level representation of wind drag forcings on the hull through NCOS ONLINE wind models
- Using NCOS ONLINE turning heel models for each ship, according to experiences with full bridge simulation of same class of vessels

Loading conditions were varied to represent the different transit scenarios for each class of vessel, through implementing statistical data of similar vessels using NCOS ONLINE, and accepted industry guideline of PIANC [3]. In general, for same loading draft, the metacentric heights (GM) are expected to vary based on the gauge level of bunker fuel, arrangement of cargo in tanks and loading plan of containers within hold and deck. In order to achieve this, two different GM levels were considered for the container ship and bulk carrier.

In addition, for the case of container ship, based on rough weight of containers carrying, the number of tiers on the deck would be different. Typically, low GM happens when carrying light containers and associated to high number of stacks on deck, and high GM happens for carrying heavy containers with low number of stacks on deck. Thus, the lateral windage area of containerships are also varied scenario based. As the cargo load is not a significant portion of total vessel displacement weight for cruise ships, and they usually travel in close to design condition, only one loading scenario (a single GM value) was assumed for the cruise ship. The applied GM values are reported in Appendix A.

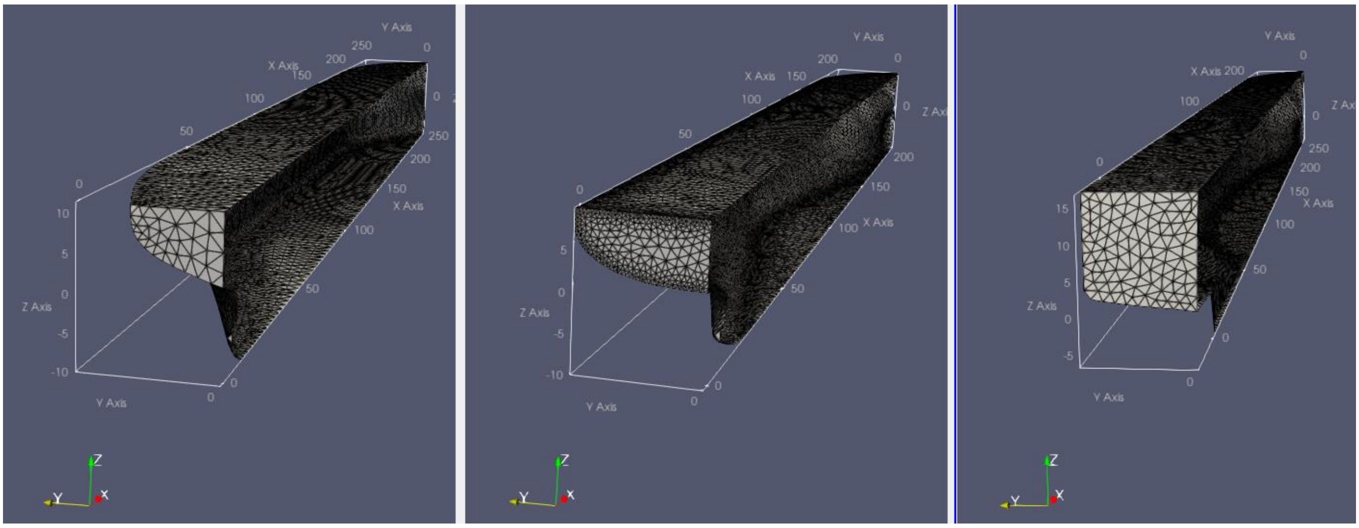



*Figure 16 Hull grids of the three vessels used in the study, i.e., bulk carrier (left), container vessel (center), and cruise ship (right). From FORCE's database.*

# 6 PHYSICS-BASED NAVIGATION MODEL

## 6.1 The NCOS ONLINE

The under-keel clearance related operability analysis of the existing MMC was undertaken by using DHI / Seaport OPX's Nonlinear Channel Optimisation Simulator NCOS ONLINE software.

NCOS ONLINE is a next-generation, award-winning 100% physics-science based active port and vessel traffic management system developed by DHI / Seaport OPX that provides risk-based decision support to all aspects of marine side operations from berth to seas, such as safe scheduling of navigation and towage and safe vessel moorings at berth. In the present capacity study, the **NCOS ONLINE UKC** module was applied (Figure 17). The engine room of NCOS ONLINE UKC module leverages the unique combination of DHI's industry standard marine hydrodynamic modelling software MIKE 21/3 (Section 4), and FORCE's state-of-the-art seakeeping and manoeuvre response engine SimFlex4. The vessel response engine uses a full 3D panel model of each vessel (Figure 16).

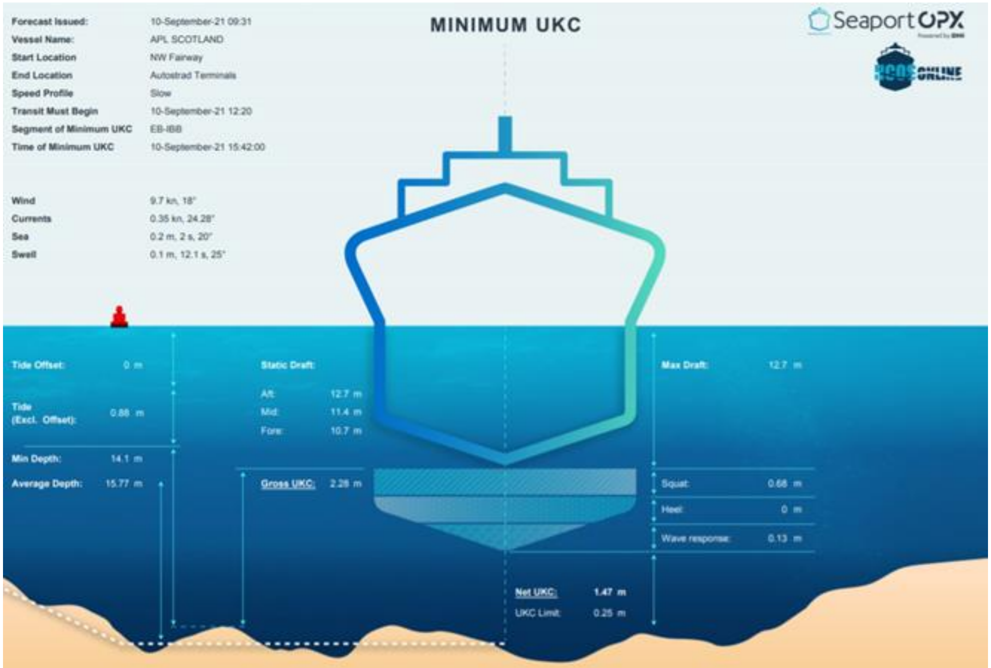



*Figure 17 Example of an extract of an NCOS ONLINE transit planning report. Used operationally and in strategic capacity assessments (as in this in present study).*

The wave-induced frequency response component of NCOS ONLIE utilises the seakeeping code S-Omega by FORCE. S-Omega is a state-of-the-art, 3D linear radiation-diffraction panel code, which computes the linear motion response amplitude operators (RAOs) of vessel responses to unit wave amplitude. Second order vertical motions are also included. The vertical motions are calculated as the combined first and second order motions induced by the waves, including contributions from heave, roll and pitch. The vertical excursions are determined at any user-specified number of locations on the bottom and extremities of the vessel hull.

Squat calculations are made for through-water vessel speeds by dynamically updating the relative vessel speed based on the spatially varying current fields. The influence of restricted channel geometries on channel blockage and subsequent vessel squat is accounted for by calculating the restricted channel cross-section area based on the actual water level condition and spatial variables describing the variation in the restricted channel geometry.

NCOS ONLINE is coupled with hydrodynamic and spectral wave modelling results to carry out long-term time-domain simulations of inbound and outbound vessel transits across multiple years of detailed spatially varying metocean data including waves, currents, tides and winds.

The following sections presents the adopted configuration of the NCOS ONLINE model to evaluate the operability of the MMC.

## 6.2 Channel mesh and bathymetry

Figure 18 displays how the MMC was discretised spatially in NCOS ONLINE. The mesh was rectangular with only one cell across the width of the channel. Except near Malamocco, the channel extremities followed the 11.50 mIGM42-depth contour line. The longitudinal length of the cells was 180 m approximately. Cell width was around 200 m near Malamocco, then it decreased gradually to 100 m along the bend in San Leonardo. Along the N-S alignment towards Marghera, the cell width reduced further to 60 m.


*Figure 18 Mesh adopted for the spatial discretization of the MMC. Image ©Google Earth*

The applied bathymetric model consisted of an input file with two water depth values calculated for each cell of the mesh, i.e., the *average* water depth and the *minimum* water depth. The former was calculated as the mean value of the bathymetry data enclosed in a cell. The latter was defined as the shallowest of the bathymetry points within the cell. Figure 19 shows the average and minimum depth profile along the centreline of the mesh. The minimum (shallowest) depth along the entire MMC was 11.50 mIGM42 (11.58 mMSL).

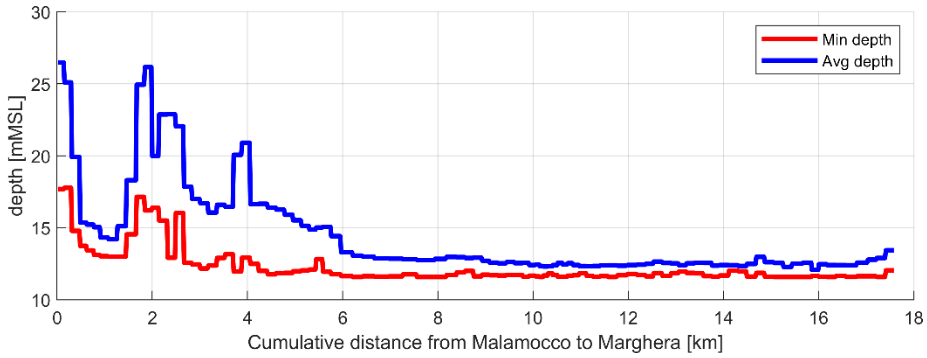



*Figure 19 Model bathymetry profile along the centerline of the discretized MMC. Minimum and average depths are shown in red and blue respectively.*

## 6.3 Transit track and speed profile

Inbound and outbound transits of the three vessels were simulated separately. An inbound transit was defined as the vessel sailing from Malamocco to Marghera, while the outbound transit was defined as the opposite transit.

The centreline of the channel was defined as the vessel track, for both inbound and outbound transits. The overground speed profile for an inbound transit is displayed in Figure 20. The outbound speed profile is the reverse of the inbound speed profile. Moving inbound, the speed was kept constant at 10 knots initially. Along the bend at San Leonardo, the speed linearly decreased to the value of 6.5 knots that was kept along until the end of the transit in Marghera.

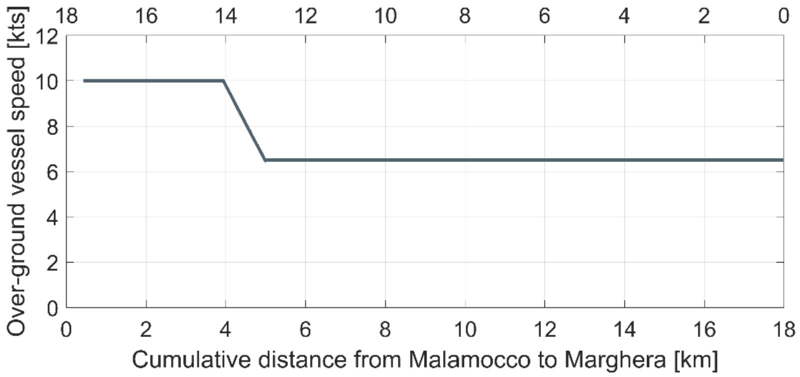



*Figure 20 Vessel speed profile used in the study.*

## 6.4 Vertical vessel motions

This section describes on how the vertical vessel motions induced by waves, squat and dynamic heel were determined by the NCOS ONLINE UKC module. These vertical motions contributed to the under-keel clearance as explained in Section 6.6.

### 6.4.1 Wave-induced vertical motions

S-Omega (Section 6.1) applies a 3D Boundary Element Method incorporating the effects of a combined sea/swell sea state acting on the full panelised hull of the design vessel, taken in combination with the vessel's hydrostatics, vessel speed, the local water depth and 2$^{nd}$ order set-down.

S-Omega was used to calculate the linear motion response amplitude operators (RAO's) of response to unit wave amplitude for the 3D vessel hull of the design vessel. RAO's were calculated for combinations of speeds, depths, and vessel headings.

The calculation of the grounding probability was based on the vertical motions of five (5) points representative points conveniently placed at the bottom and extremities of the hull for each vessel. Figure 21 shows the representative points for the bulk carrier as an example.

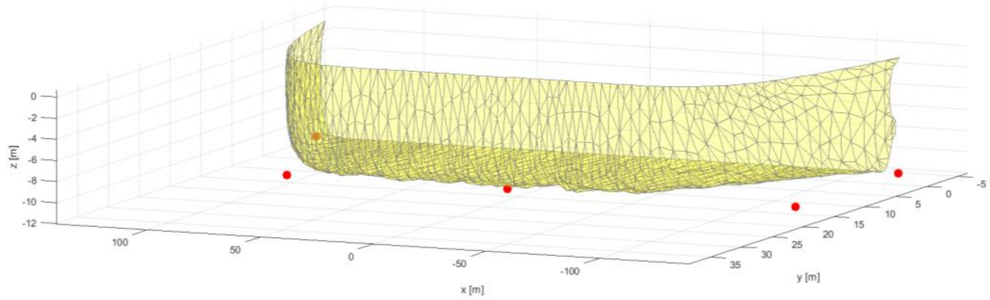



*Figure 21 Representative points of the bulk carrier hull used in the analyses.*

### 6.4.2 Squat

NCOS ONLINE calculated the vessel squat with an optimised formula that switched between various known methods (Huuska, Barrass, Yoshimura, Millward) based on speed, channel geometry and (average) water depth.

Speeds used for squat calculations were obtained from the over-ground speed profile in Figure 21 adjusted with the temporally and spatially varying current forcings. Channel geometry input was built upon a 3D-reconstruction of the channel bathymetry (Figure 22).

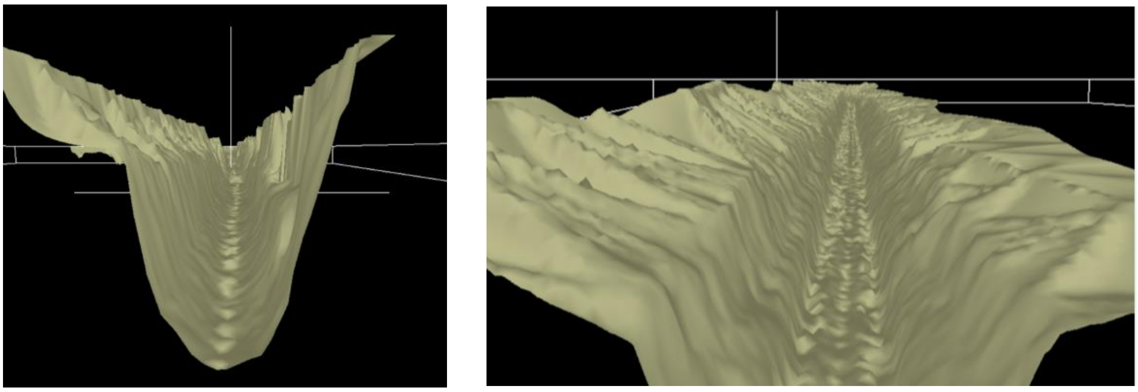


*Figure 22 Examples of 3D bathymetry of the MMC. Cross-section dimensions were used for squat calculations.*

### 6.4.3 Dynamic heel

Dynamic heel-induced vertical motions were computed as the sum of wind heel and turning heel contributions, both based on formulations in PIANC [3].

The turning heel was a function of GM and rudder angle input amongst others. The lower GM and/or the higher the rudder angle, the higher the turning heel.

Wind heel was a function of GM and vessel windage projected lateral areas amongst others. Wind heel increased with decreasing GM and/or increasing the windage area.

## 6.5 Analysed scenarios

The NCOS ONLINE simulation matrix was built upon the (3) three selected vessels, the two (2) different loading conditions (min GM and max GM), and the two (2) transit directions (inbound and outbound). Ten (10) scenarios were simulated (Table 4), as a single GM value was used for the cruise ship.

*Table 4 Scenarios analysed in the study.*

| ID | Vessel | GM | Transit direction |
|---|---|---|---|
| 1 | Bulk carrier | Min | Inbound |
| 2 | Container ship | Min | Inbound |
| 3 | Cruise ship | Min=Max | Inbound |
| 4 | Bulk carrier | Min | Outbound |
| 5 | Container ship | Min | Outbound |
| 6 | Cruise ship | Min=Max | Outbound |
| 7 | Bulk carrier | Max | Inbound |
| 8 | Cruise ship | Max | Inbound |
| 9 | Bulk carrier | Max | Outbound |
| 10 | Cruise ship | Max | Outbound |

In each scenario, NCOS ONLINE was configured to initiate a transit every 30 minutes over the full 1-year metocean hindcast period, corresponding to approximately 17,500 unique simulated voyages.

## 6.6 Transit Operability

Each individual transit simulated by NCOS ONLINE was screened for safe operability. Two metrics were used for the screening, i.e., the Under-Keel Clearance (UKC) and the Manoeuvrability Margin (MM). Both parameters represent a vertical distance between the vessel keel and the channel bed, but they are calculated under different assumptions as described in the following.

### 6.6.1 Definition of UKC

The present study adopted the definitions of UKC contributions published in PIANC [3] and reported here in Figure 23. PIANC [3] indicated how the different contributions are combined in order to calculate the (net) UKC. Therefore, the UKC was calculated in this study as:

$$UKC = D + WL - (T + S_{Max} + A + Z_{WR}) \quad (1)$$

where:

| Symbol | Description |
|---|---|
| D | Nominal channel bed level at given datum (MSL) |
| WL | Combined effects of tide and non-tidal ambient water level variations to same datum (MSL) |
| T | Static draught, here excluding static trim and list |
| $S_{Max}$ | Maximum bow or stern squat, incorporating dynamic trim |
| A | Wave response allowance, comprising the combined effects heave, roll, pitch and 2nd order wave set-down (Figure 24) |
| $Z_{WR}$ | Sinkage due to dynamic heel due to rotational motion around the vessel longitudinal axis caused by wind and vessel turning rather than waves |

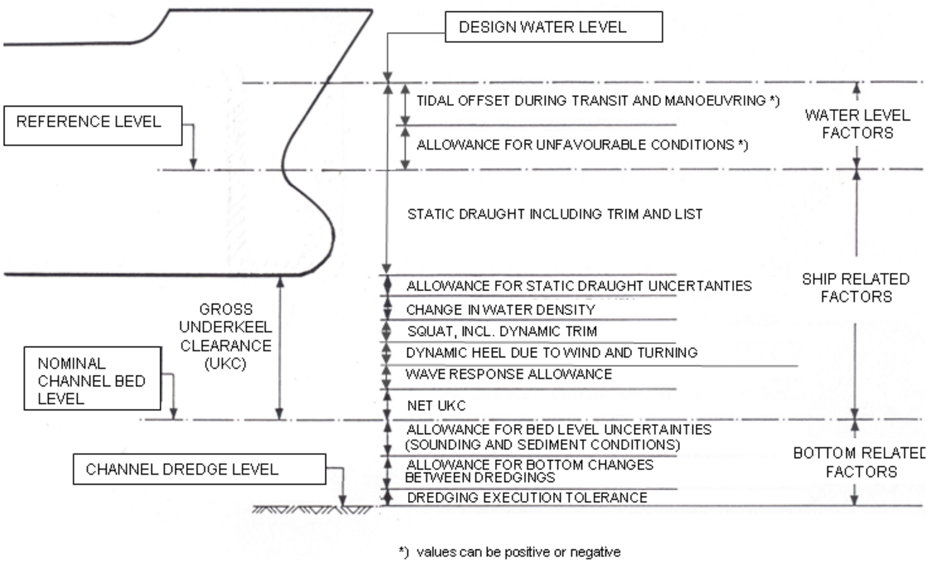



*Figure 23 Definition sketch for factors contributing to under-keel clearance from PIANC [3].*

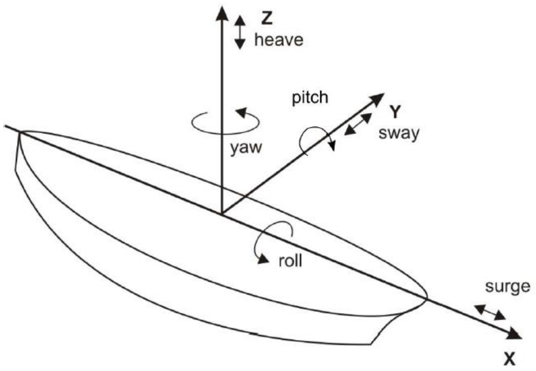



*Figure 24 Definition sketch of the six (6) degrees of freedom vessel motions.*

The following contributions, illustrated in Figure 23, are explicitly neglected in the Eq. (1) and not considered in the present study:

- Changes in water density
- Allowance for static draught uncertainties
- Trim and list components of static draft.

The net UKC margin is an important factor allowing for uncertainties in the ship-related factors when analysing UKC. PIANC [3] defines the net UKC as the minimum margin remaining between the keel of the vessel and the nominal channel bed level after subtracting the static draft, wave-induced vertical ship motions, squat and dynamic heel. Thus, the required net UKC is what is left as a *safety* margin. PIANC [3] recommends that a minimum net UKC of 0.5 m water depth under the keel is provided, but that this could be increased to 1.0m for channels with rocky seabed.

The following two assumptions have been used in the present study:

- a net UKC margin of **0.50 m** was adopted
- all bottom-related factors, as illustrated in Figure 23, have been neglected. The surveyed bed levels as provided to DHI have been assumed to be correct and representative for the objective of the study. **The existing mud interface on the channel bottom was disregarded.** Therefore, the channel depths in this study referred to nominal channel bed levels. PIANC [3] lists minimum recommendations for survey tolerance (0.1m), morphology between dredging campaigns (0.2 m) and

dredging execution tolerance (0.2-0.5m). For the purposes of the UKC study, it was considered overly conservative to add these values on top of the chosen net UKC margin of 0.50 m.

With respect to the calculation of wave response allowance, term *A* in Eq. (1), the following explanation is provided. The occurrence of the maximum vertical excursion of a vessel caused by a given wave spectrum is a probability function that converges to unity over time. As a rough estimate, any vessel located in the same sea state for more than 1 to 3 hours is almost certain to experience an event which is (in practical terms) effectively equal to the maximum possible excursion. For smaller time periods, it becomes increasingly less probable. As a result, the operability threshold is most accurately determined by a time-dependent event probability when waves are to be considered.

For this study, the time-dependent event probability threshold was defined as a 1:100 (1%) probability that any of five hull points (Section 6.4.1) was momentarily located less than 0.50 m above the nominal channel bed level at any time during a transit ($P_{UKC0.5}$ < 1%). This effectively means that a situation where any part of the vessel keel is below the net UKC during a transit is very small, hence the probability of a touch bottom event is extremely small.

The relation between the nominal channel bed level, the net UKC threshold and the 1% keel depth probability is displayed below in Figure 25.

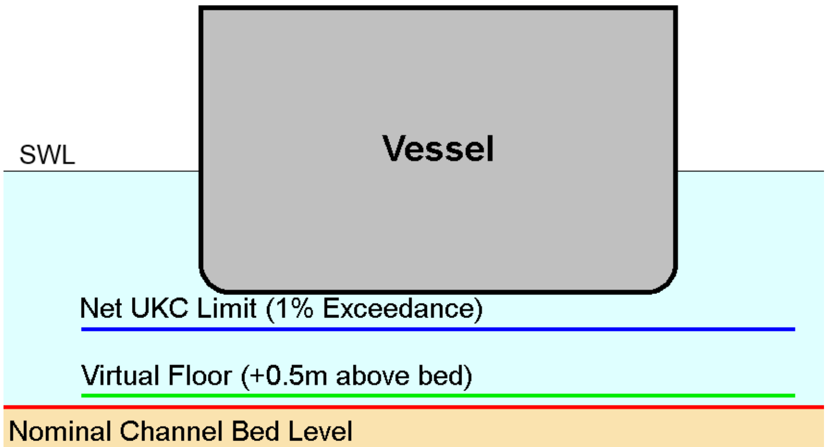



*Figure 25 Illustration of how the safe operability threshold is defined for UKC. A transit is successful w.r.t. UKC when the blue line is above the green line successful transit.*

It is noted that NCOS ONLINE UKC software has been extensively validated through full scale field measurement campaigns including large container vessels transits in highly energetic, swell dominated sea state conditions. The validation results have been published in multiple per reviewed papers.

### 6.6.2 Definition of MM

As defined in PIANC [3], the Manoeuvrability Margin (MM), is a threshold set to ensure there is enough water under the keel and flow past the rudder to allow for safe control of the ship. A vessel with a very small MM becomes very sluggish in manoeuvring and therefore has increased risks of collisions or path width excursions.
The MM threshold is calculated as

$$MM = D + WL - (T + S_{Max} + Z_{WR}) \quad (2)$$

It is noted that MM differ from UKC as it does not account for wave allowance. PIANC [3] mentions that the effect of wave-induced ship oscillations in heave, pitch and roll are not generally considered to have a significant effect on manoeuvrability.

The MM threshold used in this study was **0.60 m**.

### 6.6.3 Transit operability definition

For each of the simulated transits, NCOS ONLINE returned a time series of vessel speed, position, encountered metocean conditions, induced responses, UKC and MM. The time series of UKC and MM were screened to assess the operability of the transit as in Table 5:

*Table 5 Operability transit criteria applied in the study.*

| Parameter | UKC (m) | MM (m) |
|---|---|---|
| **Transit operable** | **> 0.50 m** | **> 0.60 m** |
| **Transit inoperable** | **< 0.50 m** | **< 0.60 m** |

With respect to UKC and MM calculations and derived operability, the following is noted:

- The *minimum* water depth was used in the computation of UKC in Eq. (1)
- The *average* water depth value was applied in Eq. (2) for MM

As the differences between these two depth values were significant, the operability assessment was mainly determined by the UKC threshold.

# 7 RESULTS

This section presents the results of the study. The analyses were based on the operability assessment of each simulated transit, according to the definitions given in Section 6.6.3. Examples of such screening are also provided in this section.

The following considerations should be kept in mind:

- The operability assessment was based on under-keel clearance factors only, calculating UKC and MM for grounding and manoeuvrability risk respectively.
- In the simulated transits, a grounding event did not necessarily mean that the vessel touched the channel bed, rather that UKC was less than the safety margin of 0.50 m.
- Wind induced-vessel drift was *not* modelled in the NCOS ONLINE UKC module. Vessels transit along the centreline of the channel with the speed profile shown in Figure 20. The fact that NCOS ONLINE calculates the UKC with respect to the minimum water depth of a cell was thus a measure to conservatively account for potential drift towards the shallower sides of the discretized channel, where depths were around 11.50 mIGM42.
- In the simulated transits, wind induced heel is included.
- Channel bank-effects were not modelled in NCOS ONLINE UKC module.

## 7.1 Examples of vessel transit screening

Figure 26 shows examples of results for a bulk carrier during an inbound transit. The different colours represent the calculated contributions to the vertical vessel motions. The red dashed line is the net UKC margin of 0.50 m. The cyan area represents the available under-keel clearance.

The first transit was operable as UKC was above the safety margin of 0.50 m and MM was above 0.60 m. Graphically, this means that the *entire* red dashed line lies within the cyan area. On the contrary, an example of inoperable transit also presented in Figure 26, where the available UKC was below 0.50 m from near San Leonardo until Marghera.

The results of the transit simulations in general support following immediate conclusions:

- wave-induced motions were significant only near Malamocco, where however the operability is generally not a concern as it is due to the large depths. During the transit displayed in Figure 26, the significant wave height was 1.34m, but it reduced considerably along the transit, with a value of 0.67 m near San Leonardo and 0.39 m near Fusina.
- dynamic heel was generally very small. The turning heel prevailed over the wind heel component.
- squat was the main contribution to the total vertical vessel movement.

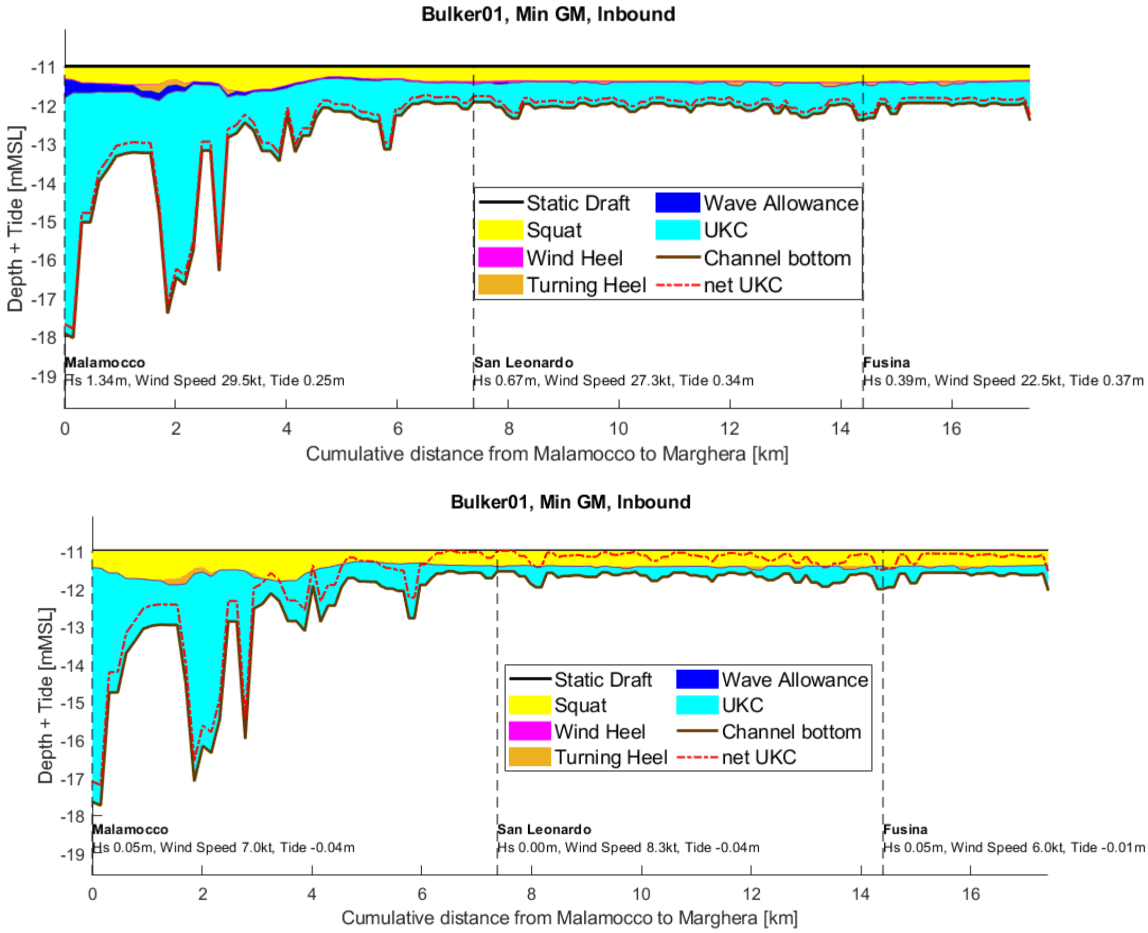



*Figure 26 Examples of simulated bulk carrier transits along the MMC. Operable (upper panel) and inoperable conditions (lower panel). The modelled contributions to vessel vertical motions are shown with different colors.*

## 7.2 Total operability

The total operability was defined as the number of operable transits relative to the total number of transits. The calculated operability levels for the three vessels are listed in Table 6, where results for minimum and maximum loading conditions are combined. It is concluded that:

- Very similar results were obtained for the bulk carrier and the container vessel. The slight difference in the outbound transits was due to a higher wind heel of the container near Motte di Volpego when heading south. The container vessel had a larger windage area compared to the bulk carrier (Appendix A).

- For the bulk carrier and the container vessel, inbound transits were generally more operable than outbound transits. The reason was the more frequent north-going currents (see Section 4.3), which reduced the speed through water, hence the squat-induced vertical motion
- All simulated transits with the cruise ship succeeded, i.e., UKC was always above 0.50 m as well as MM was always larger than 0.60 m. It is reminded that the draft of the cruise was 7.85 m, hence much smaller than the 11.00 m draft of the bulk carrier and the container vessel. Nevertheless, it could *not* be concluded that no operability issues existed for the navigation of cruise vessels along the MMC. Manoeuvrability of the cruise might be challenged by wind-induced drift, which was not included in this study. Although the minimum water depth was conservatively used in the UKC calculations, cruises might drift towards shallower areas outside the modelled channel with increased risk of grounding.

The generally low operability is discussed in the following. The values in Table 6 represent the *bulk* probabilities of success over *all* simulated transits during a full year, including for example the ones initiated at low tides. In the next section, the same results will be broken down with respect to high-tide time, quantifying thus the transit feasibility under more realistic operational conditions.
The reminder of this section will focus on the results of the bulk carrier and the container vessel simulations.

*Table 6 Summary of operability assessment. Results for inbound and outbound transits of the bulk carrier, the container vessel and cruise ship (Table 3).*

| Vessel | Transit | Total operability |
|---|---|---|
| Bulk carrier | Inbound | 11 % |
| | Outbound | 8 % |
| Container vessel | Inbound | 11 % |
| | Outbound | 7 % |
| Cruise ship | Inbound | 100 % |
| | Outbound | 100 % |

## 7.3 Operability relative to high-tide time

Figure 27 illustrates the dependency of tidal stage on the channel operability for both inbound and outbound transits of both the bulk carrier and the container vessel. The operable voyages determined by NCOS ONLINE over the 1-year period were sorted based on their start time relative to the closest high-tide time. The reference tidal level, obtained from the hindcast (Section 4), was extracted at Punta della Salute for both inbound and outbound transits.

This analysis was made by identifying the start time for all transits, and for each ½-hour start 'slot' (e.g., 2 hours after high tide) the number of operable respectively inoperable transits were found. As an example, approximately 40% of the inbound transits of the bulk carrier starting 2.5 hours before high tide was operable, therefore the (-)2.5 hour-bin was associated with an operability of 40% approximately.

Based on Figure 27, the following conclusions can be made:

- For inbound transits, the higher levels of operability were in the range 40-50%. These levels were reached when the vessels entered from Malamocco in a time window between 2.5 and 0.5 hours before the high tide at Punta della Salute. In particular, the highest operability of 50% approximately was found for the transits starting between 1.5 and 1 hour before the high tide. These results are aligned with the finding in Figure 8, where it is shown that the high tide in Malamocco occurs around 70 mins earlier than in Punta della Salute.
- For outbound transits, operability was generally lower. The highest operability level was 35% approximately, reached when the bulk carrier and the container vessel left Marghera no earlier than 30 mins before the high tide.
- Inbound and outbound transits starting at low tide in Punta della Salute were inoperable for the 11m draft vessels.

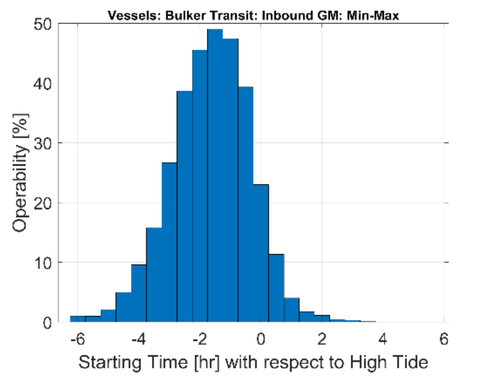
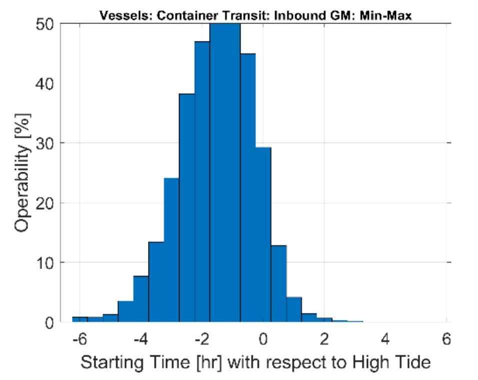
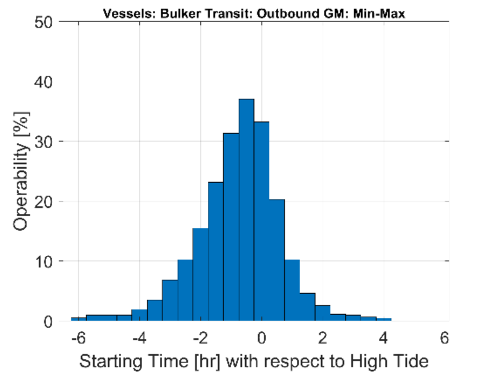
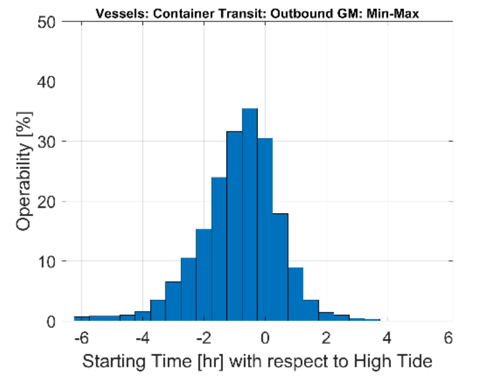
| | Bulk carrier | Container vessel |
|---|---|---|
| **Inbound** |  |  |
| **Outbound** |  |  |

*Figure 27 Operability results for the bulk carrier and the container vessel relative to time of high-tide at Punta della Salute.*

## 7.4 Operability along the channel

Bulk carrier and container vessel transits were analysed to identify how many failures (UKC < 0.50 m and/or MM < 0.60 m) took place in each cell of the mesh. In this way, a spatial distribution of the operability along the MMC was obtained. Figure 28 and Figure 29 show the results obtained for the bulk carrier and the container vessel, respectively. It was found that no specific section of the channel restrained the operability. As expected, operability was generally lower along the bend and along the N-S alignment of the channel, where shallower water depths were located. Failures occurred also between Malamocco and San Leonardo, due to a combination of turning heel and small minimum depth values.

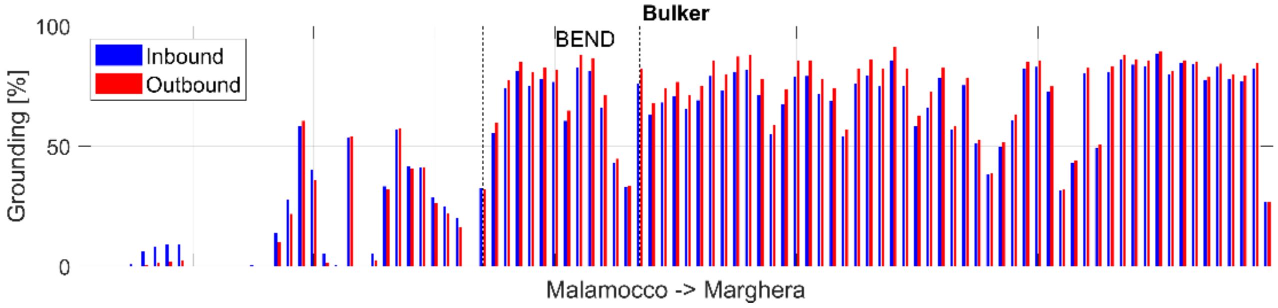



*Figure 28 Occurrence of failures along the MMC during inbound and outbound transits of the bulk carrier*

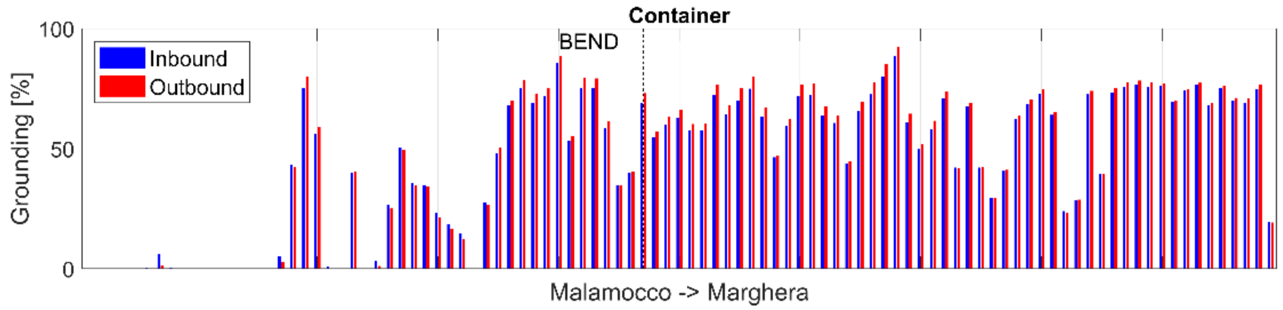



*Figure 29 Occurrence of failures along the MMC during inbound and outbound transits of the container vessel.*

## 7.5 Limiting meteomarine conditions

As waves and currents are not significant along the MMC, operability is mainly driven by water level and winds.

In order to visualize ranges of safe operability, the transits simulated with the bulk carrier and the container vessel were organized in the water level-wind graph shown in Figure 30. Each transit is represented with a point. The coordinates of each point refer to the water level and the wind speed occurred at Punta della Salute at the transit starting time. A point is red if the transit was not operable, whereas it is green if the transit was operable. Two main conclusions can be derived:

- Operability had a strong dependency on the water level. In this regard, almost all transits succeeded when they were initiated with a water level at Punta della Salute above +0.50 mMSL (+0.82 mZMPS)
- Operability seems not depending on the wind speed, as both succeeded and failed transits were found for a given wind speed. As already mentioned, this circumstance implies only that the wind-induced heel did not have a significant impact on the operability. As already explained, wind (speed) is expected to influence the results when accounting for vessel drift

It is also noted that the quantified relation between operability and water level was strictly related to the UKC margin of 0.50 m applied in the analyses. If a smaller safety UKC margin was used, transits would have succeeded with a water level at Punta della Salute lower than +0.50 mMSL (+0.82 mZMPS). With the probabilistic wave allowance being not very significant, the under-keel clearance can be practically approximated with factors such as water depth, water level, squat, and heel. Therefore, it can be expected that the minimum water level threshold at Punta della Salute follows the net UKC margin value almost linearly. For example, if the net UKC was 0.25 m, transit could succeed with a water level of at least 0.25 mMSL (+0.57 mZMPS). In the scenario with net UKC = 0m, corresponding to a realistic situation where vessels are allowed to touch the mud interface on the MMC bed, transits would be operable with a water level above 0 mMSL (+0.32 mZMPS) at Punta della Salute. This last consideration is in agreement with the channel navigability regulations in Table 2.

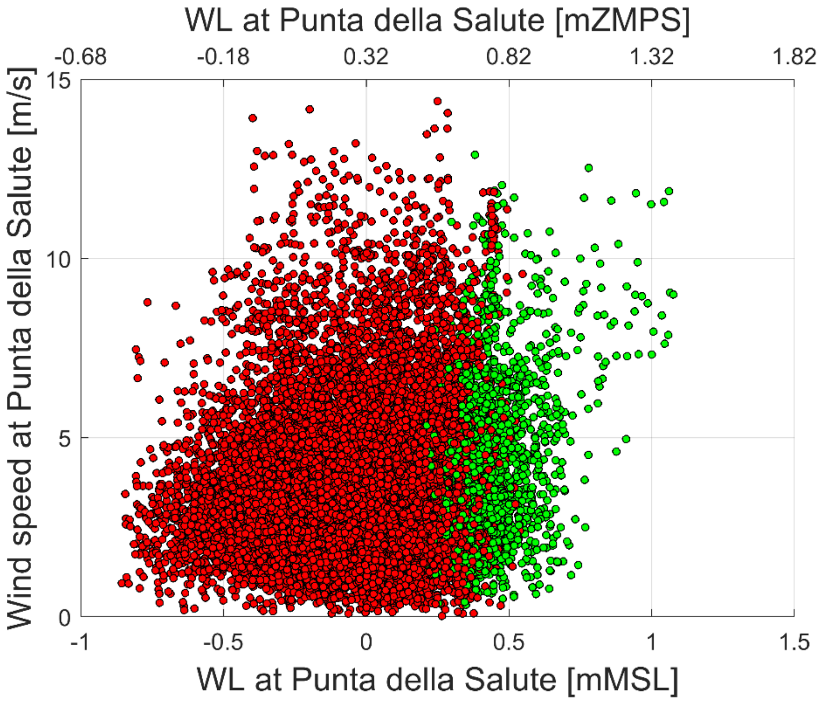



*Figure 30 Combination of water level and wind speed at Punta della Salute at the departure time of the simulated transits. Colours indicate the outcome of the operability assessment for each transit, i.e., red for inoperable and green for operable transit.*

## 7.6 Transit screening for FORCE's fast-time simulations

The comprehensive NCOS ONLINE results were also scrutinized to help identifying individual transits that could be included to the FORCE's fast-time simulation plan, for both the bulk carrier and container vessel. In FORCE simulations, the vessel manoeuvrability was modelled explicitly, including wind-induced vessel drift and bank-effects.

The FORCE's fast-time analyses did not cover a full year as in present study, but only selected transits [4]. The delivery of this screening was a list of transit departure times that were used by FORCE to extract the associated environmental forcings from the 1-year hindcast database. Those forcings were then applied in the fast-time simulation.

In agreement with FORCE, the screening focused on those transits in near-critical manoeuvrability conditions with MM between 0.60 m (applied safety margin) and 1.10 m (10% of the vessel draft).

Many of these transits failed the UKC criterion (UKC < 0.50 m). With FORCE's fast-time method, it was verified whether, for those transits, the vessel could actually maintain the navigation along the centreline of the channel, without thus drifting towards the shallower sides where grounding took place. This exercise, together with the FORCE's full bridge missions, could potentially lead to, for example, a relaxation of the meteomarine condition limits currently applied for the navigation along the MMC. Figure 31 displays in yellow the transits with 0.60 < MM < 1.10 m on top of the graph in Figure 30. It can be seen that the near-critical MM values generally occurred when the water level was comprised between -0.40 mMSL (-0.08 mZMPS) and +0.50 mMSL (+0.82 mZMPS).

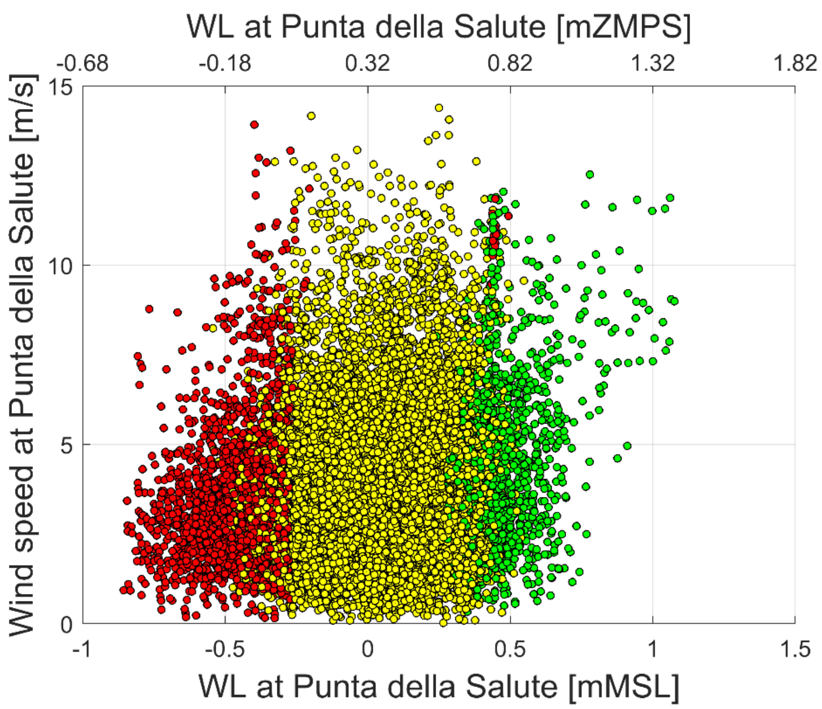



*Figure 31 Combination of water level and wind speed at Punta della Salute at the departure time of the simulated transits. Colors indicate the outcome of the operability assessment. Red for transits with UKC < 0.50 m, yellow for transits with MM comprised between 0.60 m and 1.10 m, green for transits with UKC > 0.50 m and MM > 1.10 m.*

The MM-critical transits in Figure 31 were arranged in scatter plots as in Figure 32, which is an example for the inbound bulk carrier. Those plots collect the water levels, winds and currents encountered by the vessel at every time step in which 0.60 < MM < 1.10 m during each transit. These plots facilitate the identification of metocean scenarios possibly recurring when the vessel experienced near-critical manoeuvrability conditions.  In fact, such scatter plots did not show a strong operability-related correlation between the analysed environmental conditions. Looking at the example in Figure 32, wind speeds and directions were scattered across water level and MM values. However, a pattern is recognized on the currents. For the lower limit of the water level range around -0.4 mMSL, currents with directions in the sector 345-90° with speeds in the range 0.3-0.6 m/s allowed to navigate with MM above 0.60 m. As already mentioned, this is explained with the fact that north-going currents reduced the squat of inbound vessels.

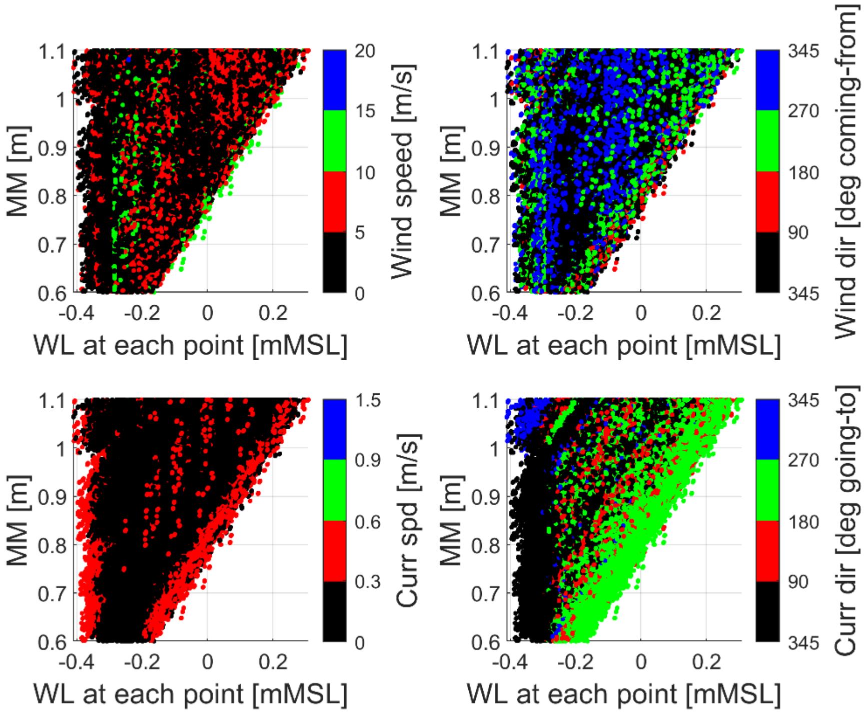



*Figure 32 Manoeuvrability margin, winds, and currents of transits with MM comprised between 0.60 m and 1.10 m.*

The transits were finally picked based on a matrix of metocean scenarios built upon two water levels (-0.20 mMSL and -0.40 mMSL), three wind speeds (5, 10, 15 m/s), two wind direction sectors (0°-90°, 90°-180°), two current speeds (0.3, 0.6 m/s), and two current direction sectors (340°-20°, 160°-200°). The list of the selected transit departure times is given in 0. The FORCE's fast-time modelling is reported in [4].

# 8 REFERENCES

[1] DHI, “Navigational Operability Assessment for the Malamocco-Marghera Channel - Meteomarine and hydrogeological characterization of Venice lagoon,” 2022.

[2] C. d. P. d. Venezia, “Ordinanza - Pescaggio massimo delle navi in navigazione nel canale Malamocco-Marghera,” 2021.

[3] PIANC, Harbour Approach Channels Design Guidelines, Bruxelles: The World Assoication for Waterborne Transport Infrastructure, 2014.

[4] FORCE Technology, “Navigational Operability Assessment For The Malamocco-Marghera Channel, Venice, Italy - Fast-time navigation simulations,” 2022.

# APPENDICES

# APPENDIX A

# NUMERICAL SHIP MODELS AND VESSEL PARTICULARS APPLIED IN THE STUDY

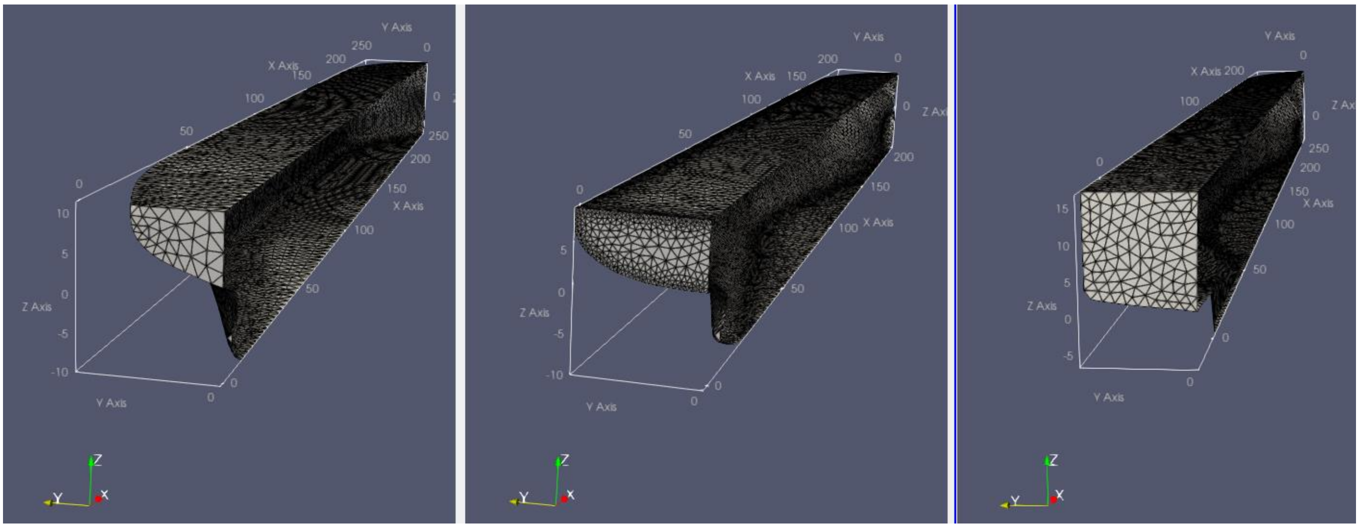


*Figure 33 Hull grids of the three vessels used in the study, i.e., bulk carrier (left), container vessel (center), and cruise ship (right). From FORCE's database.*

*Table 7 Particulars of the bulk carrier.*

| Particular | Value |
|---|---|
| LOA (m) | 260 |
| LBP (m) | 254.6 |
| Beam (m) | 37 |
| Draught (m) | 11.00 |
| Displacement (tonnes) | 86387 |
| Min GM (m) | 2.19 |
| Max GM (m) | 4.59 |
| Front Windage Area ($m^2$) | 1192 |
| Lateral Windage Area - min GM ($m^2$) | 3698 |
| Lateral Windage Area - max GM ($m^2$) | 3698 |

*Table 8 Particulars of the container vessel.*

| Particular | Value |
|---|---|
| LOA (m) | 220 |
| LBP (m) | 211 |
| Beam (m) | 32.2 |
| Draught (m) | 11.00 |
| Displacement (tonnes) | 48490 |
| Min GM (m) | 1.20 |
| Max GM (m) | 1.77 |
| Front Windage Area ($m^2$) | 1285 |
| Lateral Windage Area - min GM ($m^2$) | 5582 |
| Lateral Windage Area - max GM ($m^2$) | 4824 |

*Table 9 Particulars of the cruise ship.*

| Particular | Value |
|---|---|
| LOA (m) | 293 |
| LBP (m) | 261 |
| Beam (m) | 32.2 |
| Draught (m) | 7.85 |
| Displacement (tonnes) | 47536 |
| Min GM (m) | 1.67 |
| Max GM (m) | 1.67 |
| Front Windage Area ($m^2$) | 1780 |
| Lateral Windage Area - min GM ($m^2$) | 11101 |
| Lateral Windage Area - max GM ($m^2$) | 11101 |

*Table 10 Minimum and maximum metacentric height values (GM) applied in the study for the bulk carrier, the container ship, and the cruise ship. These GM values broadly represented possible vessel loading conditions during the navigation along the Malamocco-Marghera channel.*

| Vessel | Min GM [m] | Max GM [m] |
|---|---|---|
| Bulk carrier | 2.19 | 4.59 |
| Container ship | 1.3 | 1.77 |
| Cruise ship | 1.67 | 1.67 |

## APPENDIX B

## CANDIDATE TRANSITS FOR FORCE’S FAST TIME SIMULATIONS

| ID | Departure Time | WL nominal [m] | WS nominal [m/s] | WD nominal [°N-coming from] | CS nominal [m/s] | CD nominal [°N-going to] | MM mean [m] |
|---|---|---|---|---|---|---|---|
| 1 | '20/01/2020 05:30:00 PM' | -0.2 | 5 | 45 | 0.3 | 12.5 | 0.89 |
| 2 | '15/09/2020 05:30:00 AM' | -0.2 | 5 | 45 | 0.3 | 12.5 | 0.93 |
| 3 | '25/03/2020 07:00:00 AM' | -0.2 | 10 | 45 | 0.3 | 12.5 | 0.93 |
| 4 | '21/04/2020 06:00:00 AM' | -0.2 | 10 | 45 | 0.3 | 12.5 | 0.94 |
| 5 | '10/03/2020 07:00:00 PM' | -0.2 | 5 | 135 | 0.3 | 12.5 | 0.93 |
| 6 | '06/04/2020 01:00:00 AM' | -0.2 | 5 | 45 | 0.3 | 180 | 0.82 |
| 7 | '16/07/2020 11:30:00 PM' | -0.2 | 5 | 45 | 0.3 | 180 | 0.82 |
| 8 | '19/08/2020 01:30:00 AM' | -0.2 | 5 | 45 | 0.3 | 180 | 0.81 |
| 9 | '05/11/2020 03:30:00 PM' | -0.2 | 5 | 45 | 0.3 | 180 | 0.80 |
| 10 | '30/11/2020 02:00:00 PM' | -0.2 | 5 | 45 | 0.3 | 180 | 0.82 |
| 11 | '28/04/2020 04:30:00 AM' | -0.2 | 5 | 135 | 0.3 | 180 | 0.79 |
| 12 | '06/05/2020 01:00:00 PM' | -0.2 | 5 | 135 | 0.3 | 180 | 0.83 |
| 13 | '25/05/2020 04:30:00 PM' | -0.2 | 5 | 135 | 0.3 | 180 | 0.83 |
| 14 | '07/09/2020 06:30:00 AM' | -0.2 | 14.5 | 45 | - | 12.5 | 0.84 |
| 15 | '25/12/2020 03:00:00 PM' | -0.2 | 14.5 | 45 | - | 12.5 | 0.78 |
| 16 | '27/03/2020 04:00:00 AM' | -0.2 | 10 | 135 | - | 12.5 | 0.80 |
| 17 | '14/04/2020 11:30:00 AM' | -0.2 | 10 | 135 | - | 12.5 | 0.85 |
| 18 | '05/04/2020 11:00:00 AM' | -0.2 | 9.5 | - | 0.3 | 180 | 0.79 |
| 19 | '11/01/2020 08:30:00 PM' | -0.2 | 10 | - | 0.6 | - | 0.95 |
| 20 | '09/02/2020 07:30:00 PM' | -0.2 | 10 | - | 0.6 | - | 0.95 |
| 21 | '24/07/2020 09:00:00 AM' | -0.2 | 10 | - | 0.6 | - | 0.91 |
| 22 | '02/08/2020 06:30:00 AM' | -0.2 | 10 | - | 0.6 | - | 0.95 |
| 23 | '05/04/2020 05:00:00 PM' | -0.4 | 5 | 45 | - | 12.5 | 0.80 |
| 24 | '05/08/2020 07:00:00 AM' | -0.4 | 10 | 45 | 350 | 12.5 | 0.79 |
| 25 | '02/09/2020 06:00:00 AM' | -0.4 | 10 | 45 | 350 | 12.5 | 0.79 |