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# NAVIGATIONAL OPERABILITY ASSESSMENT FOR THE OPTIMIZED DESIGN OF MALAMOCCO-MARGHERA CHANNEL, VENICE, ITALY

## Under-keel Clearance Capacity Assessment using NCOS ONLINE

| **Activity** | | **Phase 3** |
|---|---|---|
| **Task** | | Under-keel Clearance Capacity Assessment using NCOS ONLINE |
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# EXECUTIVE SUMMARY

DHI has carried out a numerical study on the operability of the Malamocco-Marghera Channel (MMC), located in the lagoon of Venice, Italy. The operability assessment was based on under-keel clearance factors for selected design vessels. The present study was performed for an *optimized* design of the MMC. This design optimization was the outcome of a broader project which included activities such as fast-time and real-time navigation simulations, hydrodynamic and sediment transport simulations and an under-keel clearance study conducted by DHI for the *existing* configuration of the MMC [1].

The previous under-keel clearance assessment [1] was the basis of the present work. The same three design vessels were employed, i.e., a bulk carrier, a container vessel and cruise ship, with the same draughts (11.0 m, 11.0 m, and 7.85 m respectively) and loading conditions. The proposed design optimization was not expected to have a significant influence on the meteomarine conditions along the MMC, therefore the same forcing conditions in [1] were applied. The meteomarine database consisted in one (1) full year (2020) of water levels, winds, currents, and waves, modelled by DHI for the entire Venice lagoon including the MMC [2].

Compared to [1], the following changes were accounted in the present study:

- The width of the channel was increased from 50-60 m to 110-120 m in some specific areas, that is i) immediately after the bend in San Leonardo for approx. 1.2 km, ii) near the bend in Motte di Volpego for approx. 3 km, iii) near Fusina for approx. 1.0 km, and iv) near Isola delle Tresse for approx. 1.2 km
- Dredging of the areas shallower than -12.0 mIGM42
- The speed profile, identical for the three vessels, was 10 knots between Malamocco and the bend in San Leonardo, then the speed was reduced to 8 knots and kept constant until arrival in the port. In [1], the speed between San Leonardo and the arrival was 6.5 knots.

The DHI's physics based Nonlinear Channel Optimisation Simulator (NCOS ONLINE) was employed to perform this under-keel clearance study. The tool 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. Vessels transited the centreline of the channel with the prescribed speed profile.

The operability of each transit was assessed through the Under-keel Clearance (UKC) and the Manoeuvrability Margin (MM) metrics, which quantified grounding and manoeuvrability risk respectively. Both parameters 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 wind-induced heel. Wind induced-vessel drift and channel bank-effects were not included.

Consistently with the study for the existing MMC [1], the operability of each simulated transit along the design channel was assessed as in Table 1 and considering a safety UKC margin of 0.50 m. 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.

*Table 1 Operability transit criteria applied in the study*

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

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

A total operability of approximately 28% 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. The operability assessment in [1] for the existing channel had shown a total operability of approximately 9%. Therefore, the proposed channel optimization tripled the navigational operability related to under-keel clearance factors.

All simulated transits with the Cruise ship succeeded. The same observation was made for the existing channel, but the optimized channel ensures a higher safety margin due to the proposed dredging. However, the fact the no transit failures resulted from the analysis on the Cruise ship does *not* imply that no weather-related operational limits exist for cruises. In fact, manoeuvrability of cruises is limited 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 (85%) 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 80% when leaving Marghera no earlier than 30 min before the high tide at Punta della Salute. Almost all inbound and outbound transits starting at low tide in Punta della Salute were inoperable.

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 decreased locally in some areas due to higher turning heel.

Operability had a strong dependency on the water level (Figure 1). In this regard, initiating a transit with a water level above approximately +0.10 mMSL (+0.42 mZMPS) at Punta della Salute ensured a safe UKC margin of minimum 0.50 m. This occurs 40% of the time. The minimum water level threshold for safe transit was found to be +0.50 mMSL for the existing channel [1]

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.

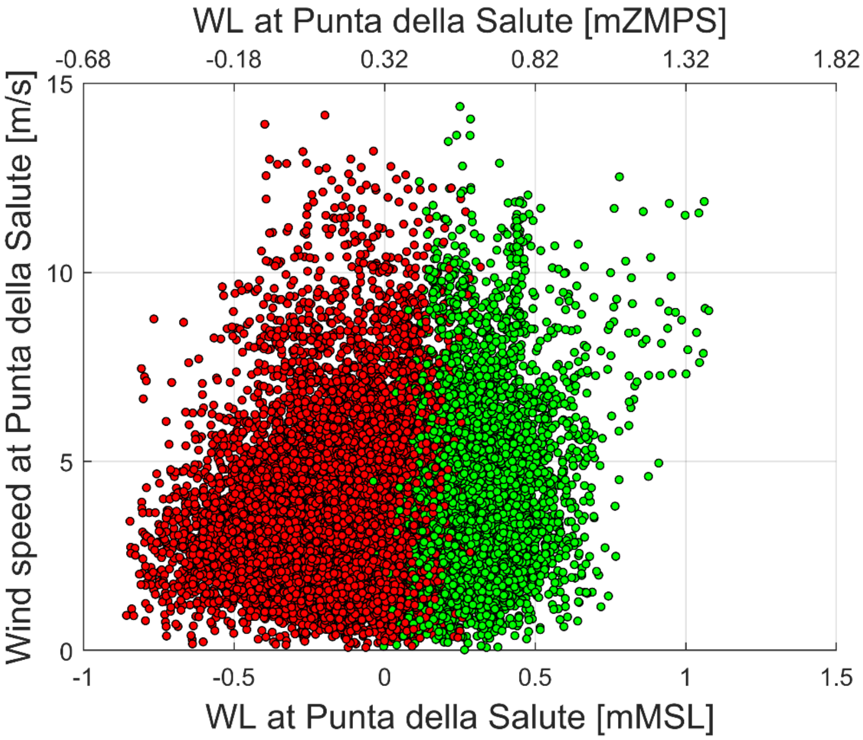

*Figure 1 Combination of water level and wind speed at Punta della Salute at the departure times of the simulated transits. Colors indicate the outcome of the operability assessment for each transit, i.e., red for inoperable and green for operable transit.*

# 1 INTRODUCTION

This report presents the **under-keel clearance** study undertaken by **DHI A/S** for an optimized design of the Malamocco-Marghera Channel, hereafter MMC, located in the lagoon of Venice, Italy (Figure 2).

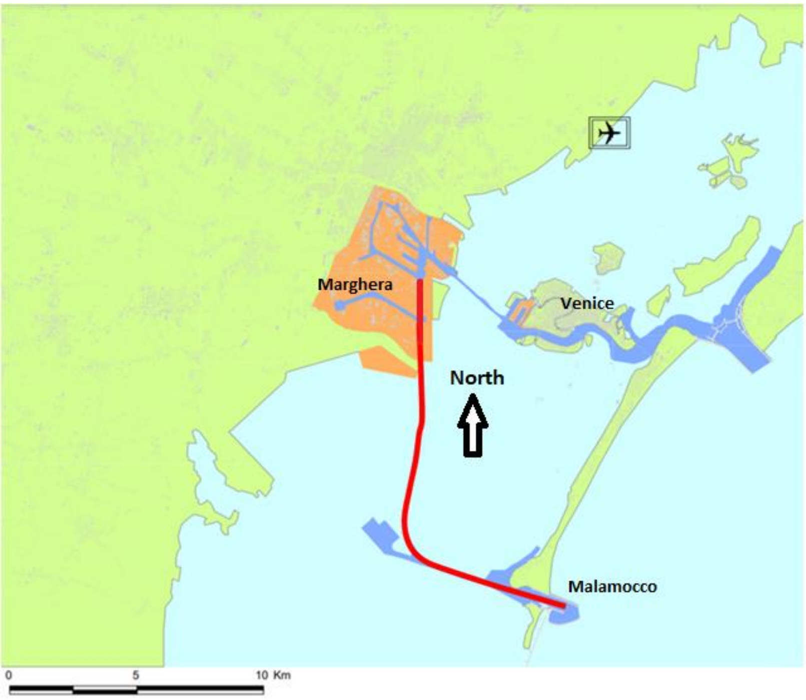

*Figure 2 Overview of the Malamocco-Marghera Channel in the lagoon of Venice. Image ©Port of Venice.*

The present study is one of the activities included in the contract scope of work and its extension undertaken by 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 di Andrea Zamariolo Ph.D. Geol.** The project activities fit into the **"Channeling the Green Deal for Venice"**, a Connecting Europe Facility European funded project (2020-2023) that tackles the current limited navigational accessibility of the ports of Venice and Chioggia, and at the same time respecting the environment of the Venice Lagoon. The project is also seeking synergies between port sustainability and mitigation of human and climate change impacts on endangered habitats. To achieve this ambitious goal, an integrated approach involving state-of-the-art modelling of navigation and meteomarine conditions including hydrodynamic / sediment transport processes was planned and implemented.

The project activities resulted in concrete engineering solutions for enhancing the channel capacity, ensuring the volume and type of vessel traffic required by Port of Venice in the future. Those solutions consisted of proposed local deepening of the channel, enlargement of cross-sections, and navigational operational recommendations, illustrated in detail in the specific deliverable.

The present operability assessment was based on vessel under-keel clearance for selected design 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. The obtained operability levels were compared with the results of the under-keel clearance study that DHI carried out for the existing MMC [1]. Improvement in operability will be highlighted and commented in the following.

# 2 THE OPTIMIZED DESIGN OF THE MALAMOCCO-MARGHERA CHANNEL

## 2.1 The existing channel

Malamocco is one of the three mouths of the Venice lagoon, and it accommodates the entry of cargo ships (Figure 3). Through a channel (red in Figure 3), 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 12.0 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 3 shows some representative locations along the MMC that are used in this report to present and discuss results, namely *Malamocco*, *San Leonardo*, *Motte di Volpego*, *Fusina*, and *Marghera*.

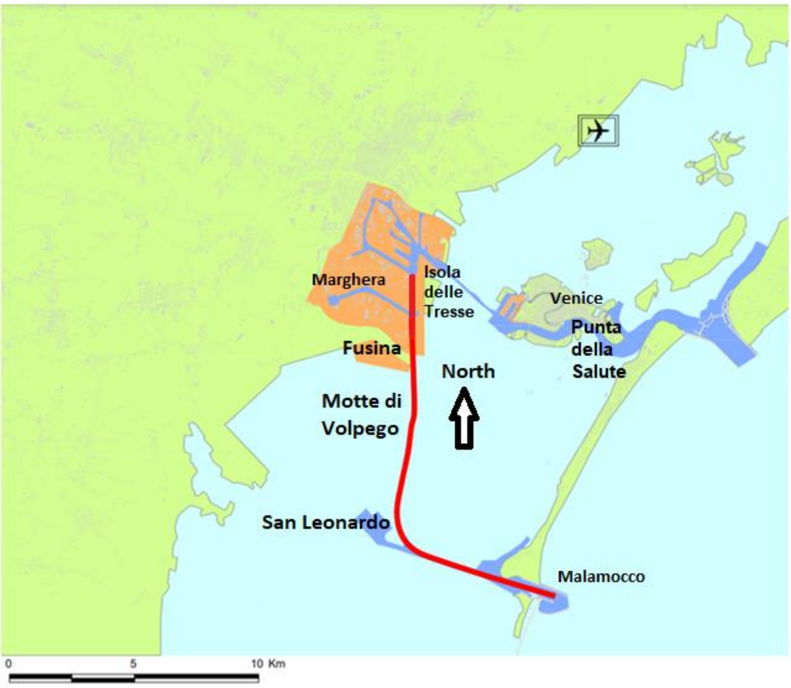

*Figure 3 Alignment of the Malamocco-Marghera Channel located in lagoon of Venice, Italy. Image ©Port of Venice.*

## 2.2 Proposed design changes

The investigations carried out by the consortium in the first phases of the project revealed the areas constraining the navigational operability along the existing MMC, for large vessels in extreme wind conditions especially. As documented in deliverable *009 – Identification of solutions*, the following design changes were identified in order to improve the MMC navigational capacity:

1. Widening of the cross-section of the channel, via dredging, from 50-60 m to 110-120 m in some specific areas. Local dredging was thus recommended i) immediately after the bend in San Leonardo for approx. 1.2 km, ii) near the bend in Motte di Volpego for approx. 3 km, iii) near Fusina for approx. 1.0 km, and iv) near Isola delle Tresse for approx. 1.2 km

2. Dredging of the areas shallower than -12.0 mIGM42

## 2.3 Bathymetry

In the present study, only the design bathymetry along the MMC was used. Data was provided by Port of Venice in WGS1984, vertical datum in IGM42 (Chart Datum, CD) and a horizontal resolution of 3 m generally. The employed bathymetric dataset reflected the proposed dredging (Section 2.2) applied on the existing bathymetry.

Figure 4 displays an overview of the bathymetry in the study area. Figure 5 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.

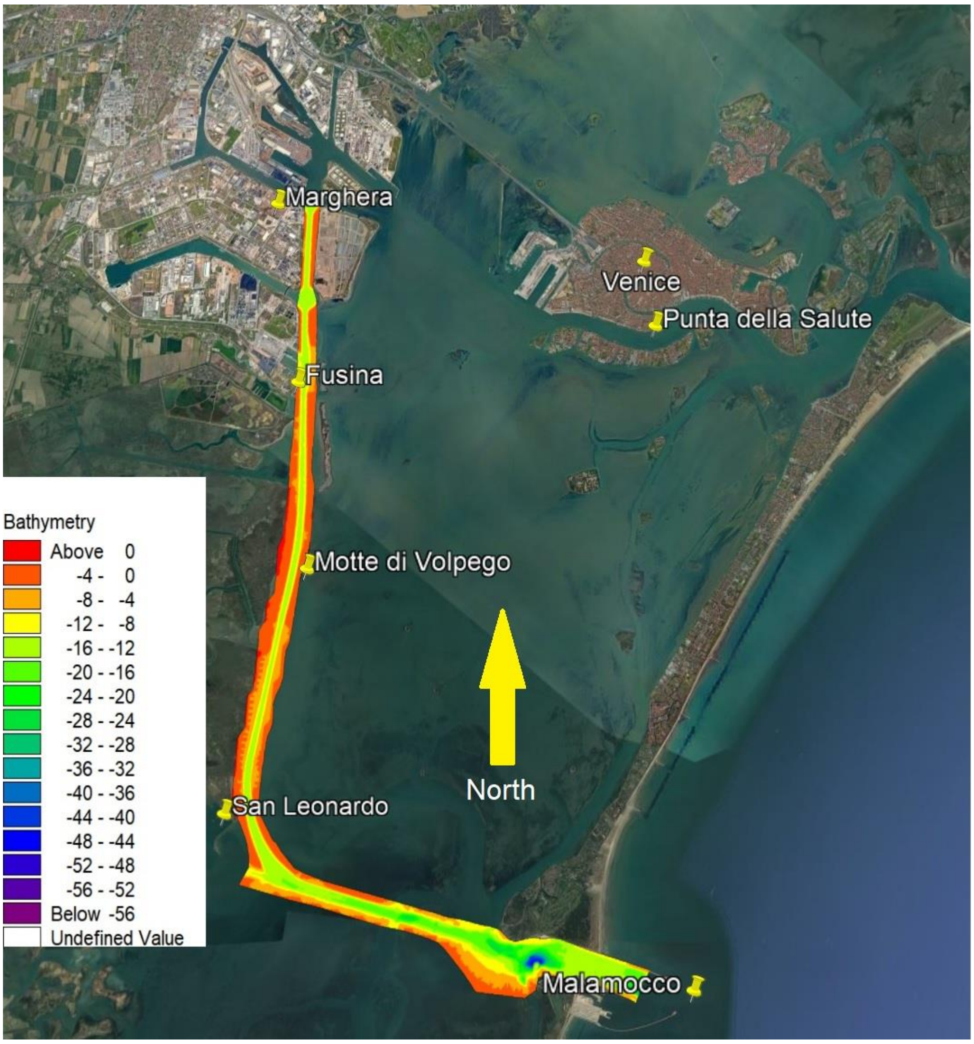

*Figure 4 Bathymetry (IGM42 datum) of the optimized MMC. Satellite background from ©Google Earth.*

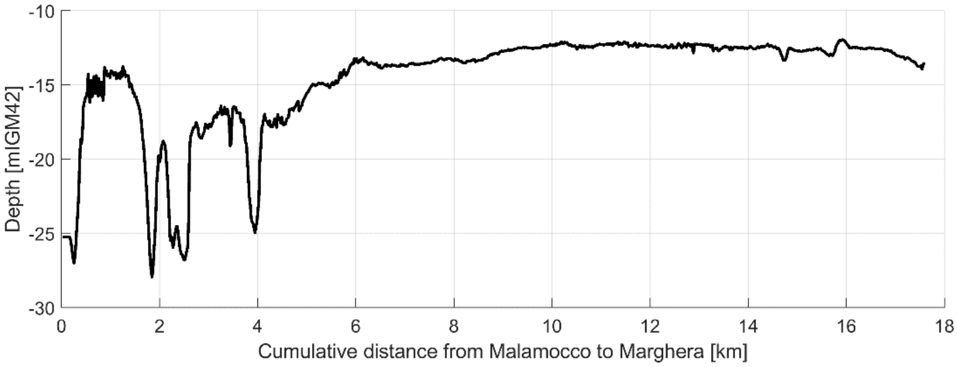

*Figure 5 Bathymetry profile along the centreline of the optimized MMC.*

## 2.4 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 6, where it can be read that $MSL = IGM42 - 0.084\ m = ZMPS - 0.32\ m$

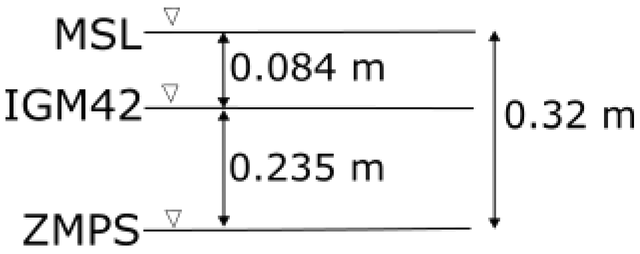

*Figure 6 Relation amongst the three relevant datums used in the study, i.e. MSL, IGM42, and ZMPS*

# 3 MODELLED METEOMARINE CONDITIONS ALONG THE OPTIMIZED 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 [2]. In fact, the metocean forcings were modelled on the entire Venice lagoon over one (1) selected representative year. As explained in [2], 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 [2] to generate model boundary conditions

In the previous [1] as well as the present under-keel clearance study, only the forcings acting along the MMC were used. The same meteomarine forcing database used in [1] for the existing MMC was applied in the present study. The assumption was that the proposed design changes would not significantly affect waves, currents and tides derived (modelled) for the existing MMC.

The meteomarine hindcast modelling for the year 2020 over the entire Venice lagoon is fully documented in [2]. The forcings modelled along the MMC are described in more detail in [1]. Here, the main observations are summarized:

- The tidal water levels varied mostly between -0.5 mZMPS and 1.0 mZMPS, with a semi-diurnal variation mostly
- Tide variations showed a time shift of 70 minutes approximately between Malamocco and Punta della Salute
- Wind directions (coming-from) were concentrated primarily in the N-E sector in 2020. The highest wind speeds were around 18 m/s.
- Currents followed the two main alignments of the MMC, i.e., ESE-WNW before San Leonardo and N-S after. 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).

- Waves entered the channel from ESE through Malamocco. After the bend in San Leonardo, waves were from either south or nearly north-east. Significant wave height was less than 0.70 m for majority of 2020 in Malamocco, reducing to less than 0.30 m near Fusina.

# 4 VESSELS USED IN THE STUDY

The operability assessment of the optimized MMC was conducted for the three vessels in Table 2. More details on the vessel particulars are given in 0. The same vessels were investigated in [1]. Using the same vessels allowed a consistent comparison with the operability levels calculated for the existing MMC, estimating thus the effects of the proposed design changes on the navigational operability related to under-keel clearance.

*Table 2 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 |

Numerical ship models were developed and provided by FORCE Technology 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 0.

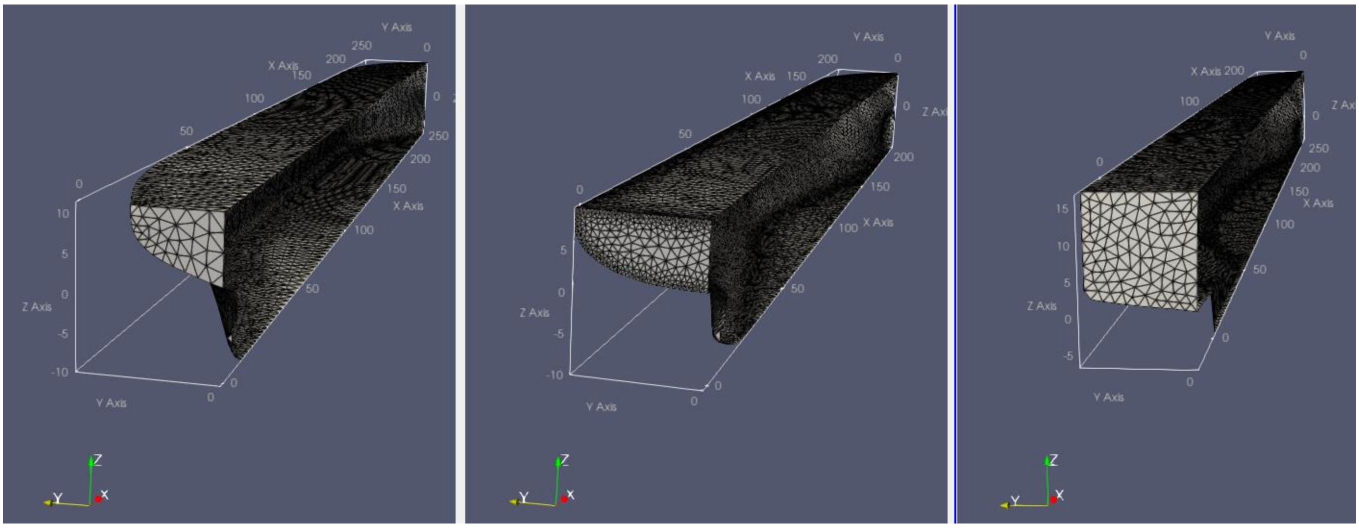

*Figure 7 Hull grids of the three vessels used in the study, i.e., bulk carrier (left), container vessel (center), and cruise ship (right). From FORCE Technology's ship database.*

# 5 PHYSICS-BASED NAVIGATION MODEL

## 5.1 The NCOS ONLINE

The under-keel clearance related operability analysis of the 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 and 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 8). The engine of NCOS ONLINE UKC module leverages the unique combination of DHI's industry standard marine hydrodynamic modelling software MIKE 21/3 (Section 3), and FORCE Technology'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 7).

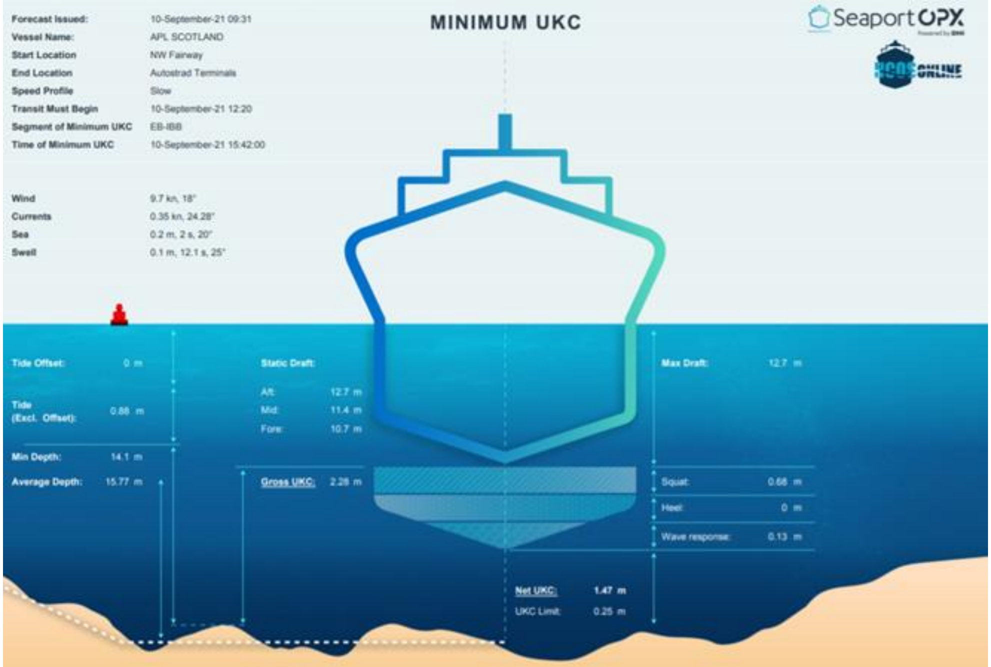

*Figure 8 Example of an extract of an NCOS ONLINE transit planning report. Used operationally and in strategic capacity assessments (as in this in present study).*

The wave-induced frequency response component of NCOS ONLINE utilises the seakeeping code S-Omega by FORCE Technology. 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.

## 5.2 Channel mesh and bathymetry

Figure 9 displays how the optimized 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 12.00 mIGM42-depth contour line. The cell width was thus around 200 m near Malamocco, it decreases to 100 m approximately along the bend at San Leonardo, and gradually to 60 m before reaching Motte di Volpego. Here the cell width increases to 100 m, and further to 120 m near Fusina. After that, the section gradually reduces to 60-70 m until arrival in Marghera. The longitudinal length of the cells was approximately 180 m along the entire channel.

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*Figure 9 Mesh adopted for the spatial discretisation of the optimized 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 10 shows the average and minimum depth profile along the centreline of the mesh. The minimum (shallowest) depth along the entire MMC was 12.00 mIGM42 (12.08 mMSL). The same figure displays the depth profiles from the bathymetry applied in [1], where the minimum depth was 11.50 mIGM42 (11.58 mMSL).

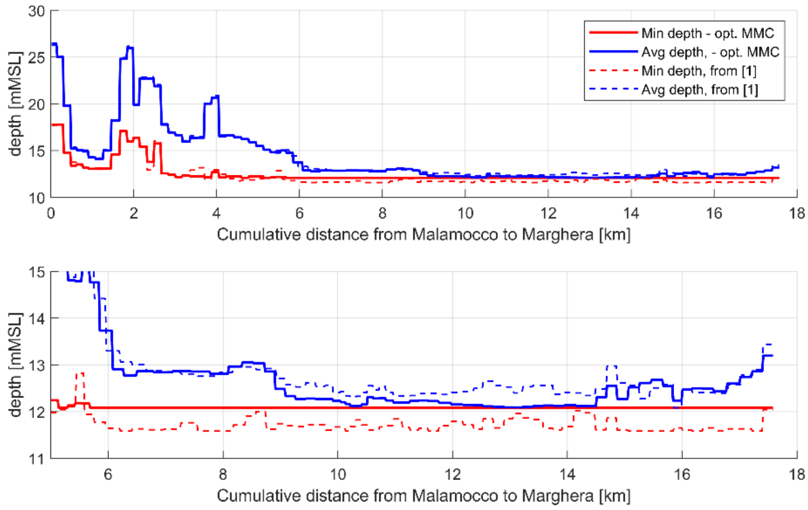

*Figure 10 Model bathymetry profile along the centreline of the discretised MMC. Minimum and average depths are shown in red and blue respectively. Solid line for the optimized MMC, dashed line for the under-keel clearance study in [1]. Upper plot: entire channel. Lower plot: close-up from near San Leonardo until arrival in Marghera.*

## 5.3 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 11. 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 8 knots that was kept along until the end of the transit in Marghera. It is noted that the operability assessment in [1] was performed with a speed of 6.5 knots after the bend.

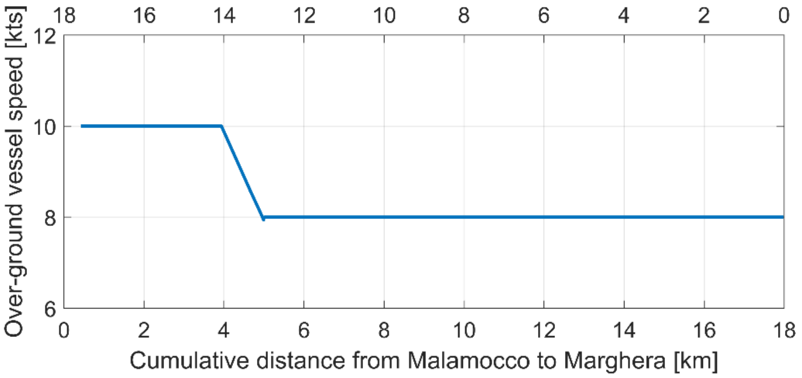

*Figure 11    Vessel speed profile used in the study.*

## 5.4 Vertical vessel motions

This section describes 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 5.6.

### 5.4.1 Wave-induced vertical motions

Waves were expected to affect operability only marginally in this study. Yet, wave -induced vertical motions were included for the sake of completeness as follows.

S-Omega 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 probabilistic wave-induced vertical motions were calculated for five (5) representative points conveniently placed at the bottom and extremities of the hull for each vessel. Figure 12 shows the representative points for the bulk carrier as an example.

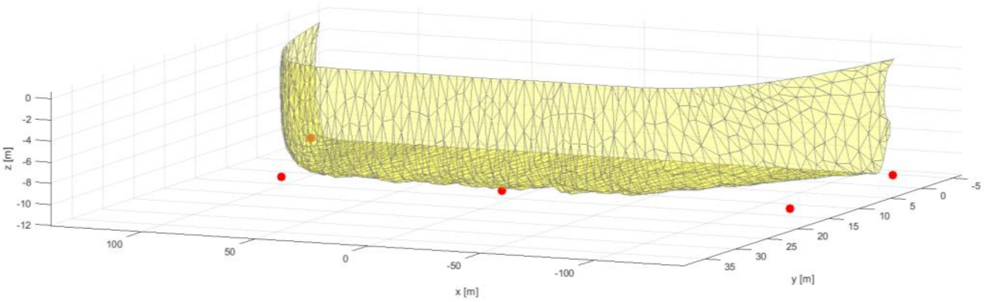

*Figure 12* *Representative points of the bulk carrier hull used in the analyses.*

### 5.4.2 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 11, adjusted with the temporally and spatially varying current forcings. Channel geometry input was built upon a 3D-reconstruction of the optimized channel bathymetry (Figure 13)

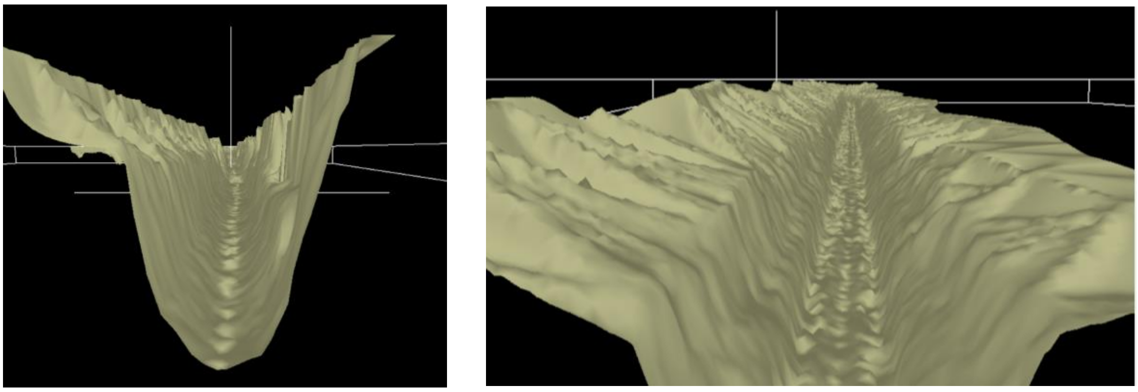

*Figure 13* *Examples of 3D bathymetry of the MMC, including the proposed design changes. Cross-section dimensions were used for squat calculations.*

### 5.4.3 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.

## 5.5 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 3), as a single GM value was used for the cruise ship.

*Table 3 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.

## 5.6 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.

### 5.6.1 Definition of UKC

The present study adopted the definitions of UKC contributions published in PIANC [3] and reported here in Figure 14. 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:

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

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 15) |
| $Z_{WR}$ | Sinkage due to dynamic heel due to rotational motion around the vessel longitudinal axis caused by wind and vessel turning rather than waves |

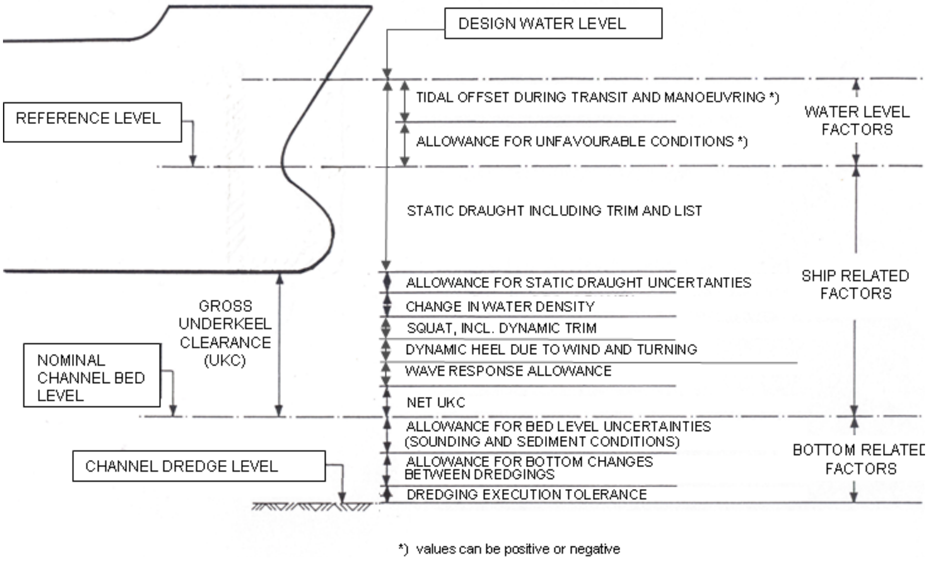

*Figure 14 Definition sketch for factors contributing to under-keel clearance from PIANC [3].*

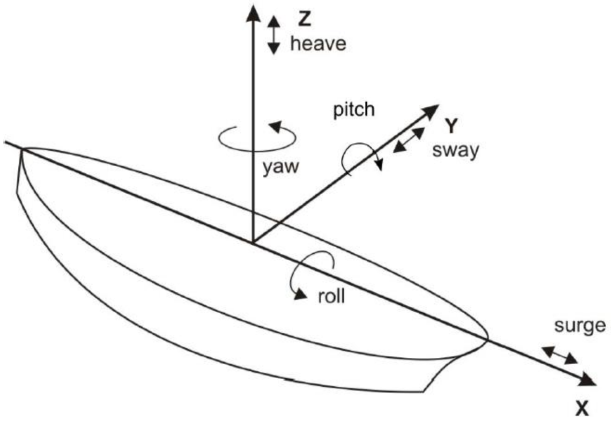

*Figure 15 Definition sketch of the six (6) degrees of freedom vessel motions.*

The following contributions, illustrated in Figure 14, 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 14, have been neglected. 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. Therefore, the channel depths in this study referred to nominal channel bed levels.

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 5.4.1) 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 16.

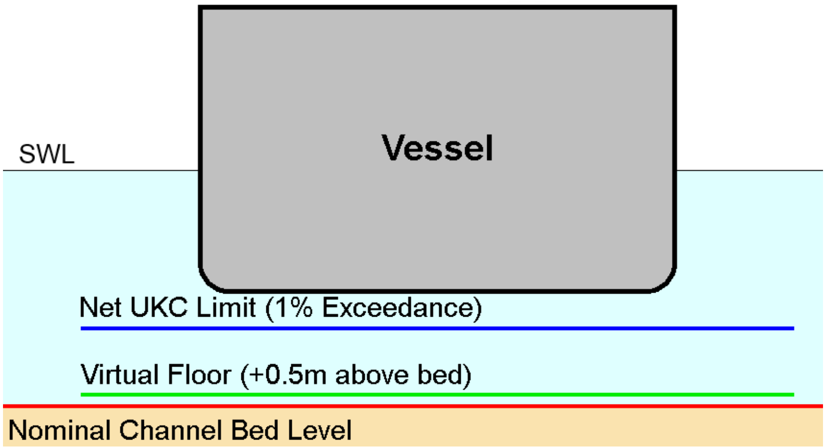

*Figure 16 Illustration of how the safe operability threshold is defined for UKC. A transit is successful w.r.t. UKC when the blue line is above the green line successful transit.*

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.

### 5.6.2 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

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

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**.

### 5.6.3 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 4. A transit was inoperable when *either* UKC *or* MM fell below the prescribed thresholds respectively. It is noted that the same thresholds for UKC and MM respectively were employed for the under-keel clearance study on the existing MMC in [1].

*Table 4 Operability transit criteria applied in the study.*

| **Parameter** | **UKC** | **MM** |
|---|---|---|
| **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.

# 6 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 5.6.3. Examples of such screening are also provided in this section. The comparison with the results obtained in [1] for the existing MMC is reported and commented.

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 transited along the centreline of the channel with the speed profile shown in Figure 11. 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 12.0 mIGM42.
- In the simulated transits, wind induced heel is included.
- Channel bank-effects were not modelled in NCOS ONLINE UKC module.

## 6.1 Examples of vessel transit screening

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 17, 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 17, 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

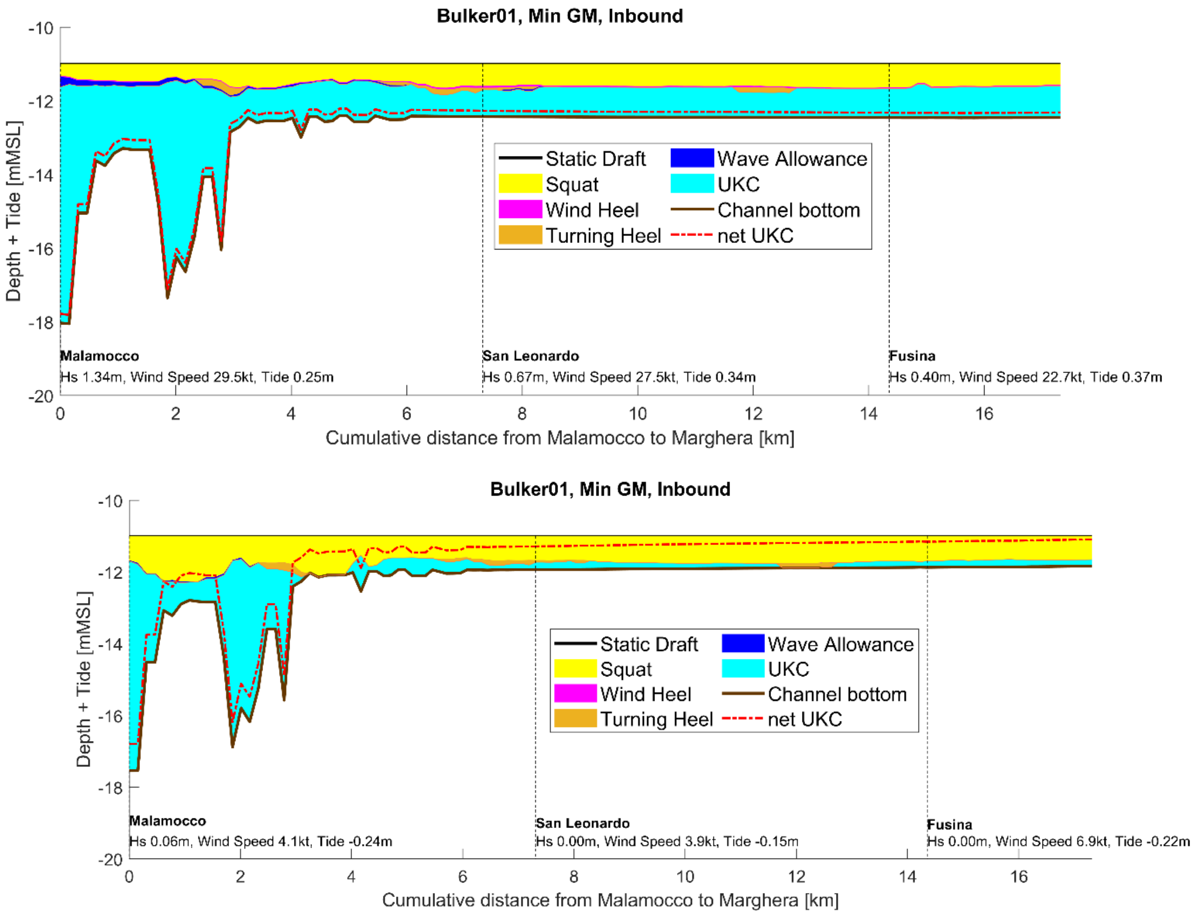

*Figure 17 Examples of simulated bulk carrier transits along the optimized MMC. Operable (upper panel) and inoperable conditions (lower panel). The modelled contributions to vessel vertical motions are shown with different colors.*

## 6.2 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 5, where results for minimum and maximum loading conditions are combined. It is concluded that:

For both bulk carrier and container vessel, the total operability increased substantially with the optimized MMC; the number of successful transits was approximately three times larger than in the study for the existing MMC [1]. The main reason for the improved operability was the deeper water of the optimized MMC, following the proposed dredging of areas shallower than 12.0 mIGM42. In

[1], the minimum (shallowest) depth was instead 11.50 mIGM42. The effect of such bathymetry change was thus more significant than the generally higher squat accounted in this study, due to the higher over-ground speed (8 knots) along the inner leg of the MMC compared to the study in [1] (6.5 knots).

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 3), which reduced the speed through water, hence the squat-induced vertical motion.

Very similar results were obtained for the bulk carrier and the container vessel. The slight difference in the outbound transit operability occurred because of the generally larger squat motions of the bulk carrier compared to the container vessel, due to higher blockage coefficient (see 0). As seen above, squat affected more the operability of the outbound transits than the inbound transits.

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. As for the existing MMC, this result was due to the smaller draft of the cruise ship, i.e., 7.85 m, compared to the 11 m draft of the bulk carrier and the container vessel. The same observation was made for the existing channel, but the optimized channel ensures a higher safety margin due to the proposed dredging. Nevertheless, this finding does *not* indicate that no inoperable scenarios exist for cruise ship. Manoeuvrability of the cruise is 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. As vessel manoeuvrability was not modelled, the improvements of the proposed design changes could not be revealed by the present operability assessment.

The values in Table 5 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 5 Summary of operability assessment for the existing (study in [1]) and optimized MMC (present study). Results for inbound and outbound transits of the bulk carrier, the container vessel and cruise ship (Table 2).*

| **Vessel** | **Transit** | **Total operability** | |
|---|---|---|---|
| | | **Existing MMC,** [1] | **Optimized MMC** |
| Bulk carrier | Inbound | 11 % | 30% |
| | Outbound | 8 % | 26% |
| Container vessel | Inbound | 11 % | 30% |
| | Outbound | 7 % | 27% |
| Cruise ship | Inbound | 100 % | 100% |
| | Outbound | 100 % | 100% |

## 6.3 Operability relative to high-tide time

Figure 18 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 3), was extracted at Punta della Salute for both inbound and outbound transits. Results for the existing MMC are reported in the same figure.

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 80% 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 80% approximately.

Based on Figure 18, the following conclusions can be made:

The proposed design optimization increased the operability at all inbound and outbound departure times w.r.t. high tide. In particular, the higher operability levels were approximately doubled compared to the ones obtained for the existing MMC [1].

For inbound transits, the maximum operability was in the range 80-90%; it was 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 approximately 85% was found for the transits starting between 1.5 and 1 hour before the high tide. These results are aligned with the finding in Section 3, where it is mentioned 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 around 80% approximately, reached when the bulk carrier and the container vessel left Marghera no earlier than 30 mins before the high tide.

Almost all inbound and outbound transits starting at low tide in Punta della Salute were inoperable for the 11 m draft vessels.

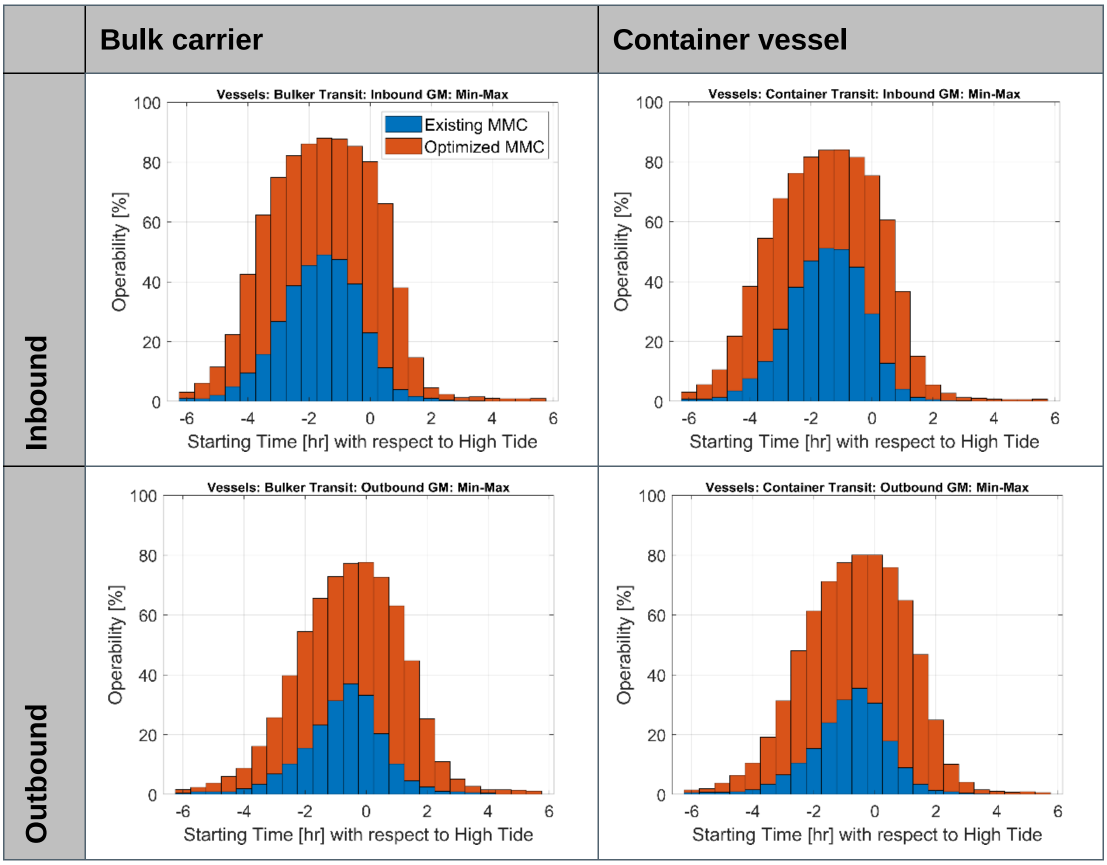

*Figure 18 Operability results for the bulk carrier and the container vessel relative to time of high-tide at Punta della Salute. Existing and optimized MMC.*

## 6.4 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 19 and Figure 20 show the results obtained for the bulk carrier and the container vessel, respectively. The same figures display the results obtained for the existing MMC in [1].

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 also occurred between Malamocco and San Leonardo.

The benefit of the proposed design optimization was clearly recognized. The operability was generally uniform along the optimized N-S alignment, where local operability reduction was observed though, due to high turning heel. In some cells before the bend in San Leonardo, the operability was lower compared to existing MMC. Again, this was due to high turning heel contribution to motions. In fact, the modelled turning heel was based on rudder angles available from *preliminary* real-time navigation simulations along the optimized MMC [4]. A refinement of the adopted rudder angle input, based on final real-time simulations, should adjust the local operability levels before the bend in San Leonardo, although a significant effect on the obtained total operability levels is not expected.

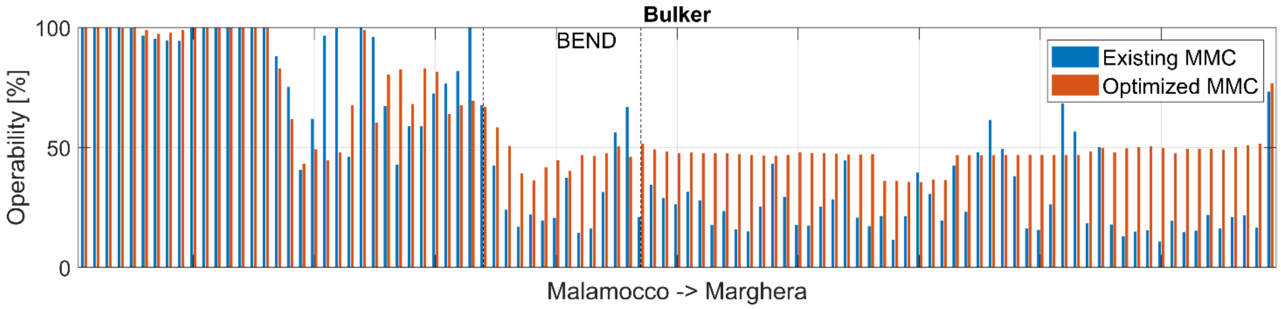

*Figure 19 Occurrence of failures along the optimized MMC combining inbound and outbound transits of the bulk carrier.*

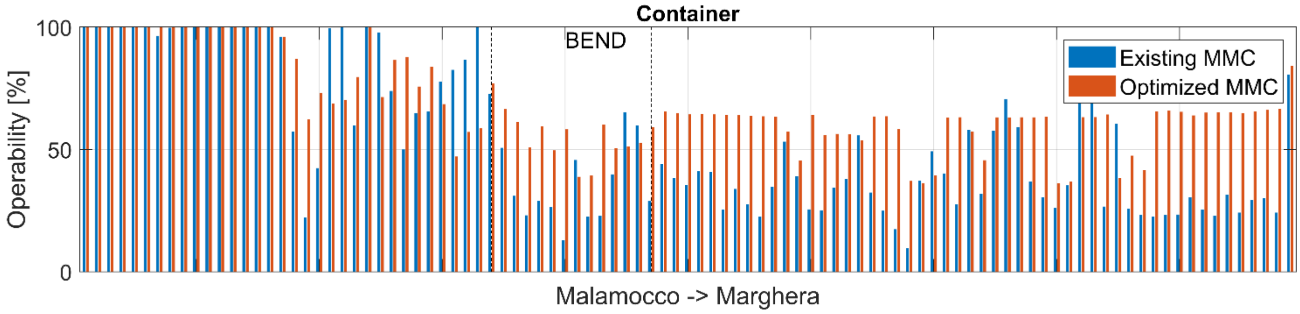

*Figure 20 Occurrence of failures along the optimized MMC combining inbound and outbound transits of the container vessel.*

## 6.5 Limiting metocean 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 21. 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 +0.10 mMSL (+0.52 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.

The same chart was presented in [1] for the existing MMC, where a minimum water level at Punta della Salute of +0.50 mMSL (+0.82 mZMPS) was identified for initiating a safe transit. Here, such safe water level threshold was thus calculated to be 0.40 m lower than in [1]. This difference followed the higher minimum water depth of the optimized MMC (12.0 mIGM42) compared to the existing MMC (11.50 mIGM42), and, on the other hand, the generally larger squat-induced vertical motions modelled in this study. In fact, with the probabilistic wave allowance being not very significant, it can be expected that the under-keel clearance can be practically calculated with combining water depth, tide, squat, and heel.

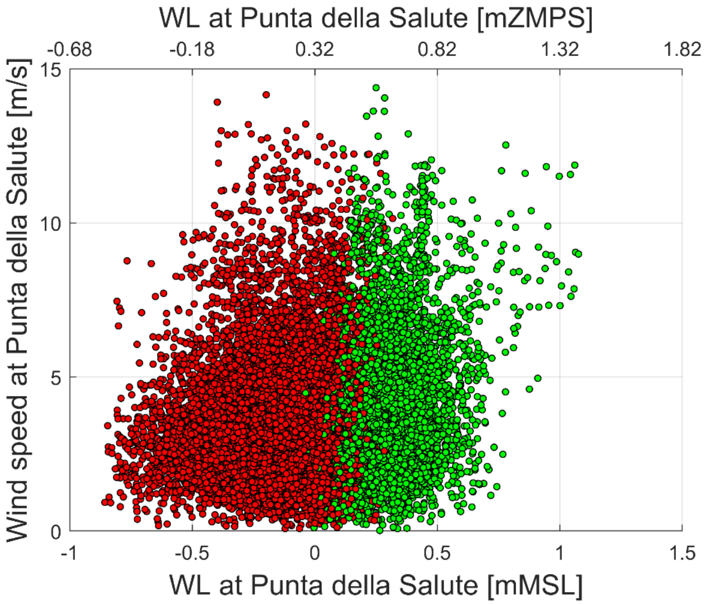

*Figure 21* *Combination of water level and wind speed at Punta della Salute at the departure time of the simulated transits. Colours indicate the outcome of the operability assessment for each transit, i.e., red for inoperable and green for operable transit.*

# 7 REFERENCES

[1] DHI, “NAVIGATIONAL OPERABILITY ASSESSMENT FOR THE MALAMOCCO-MARGHERA CHANNEL, VENICE, ITALY - Under-keel Clearance Capacity Assessment using NCOS ONLINE,” 2022.

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

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

[4] FORCE Technology, “MALAMOCCO PRELIMINAR OPTIMIZED CHANNEL FULL-MISSION SIMULATIONS,” 2022.

# APPENDICES

# APPENDIX A

# NUMERICAL SHIP MODELS AND VESSELS PARTICULARS APPLIED IN THE STUDY

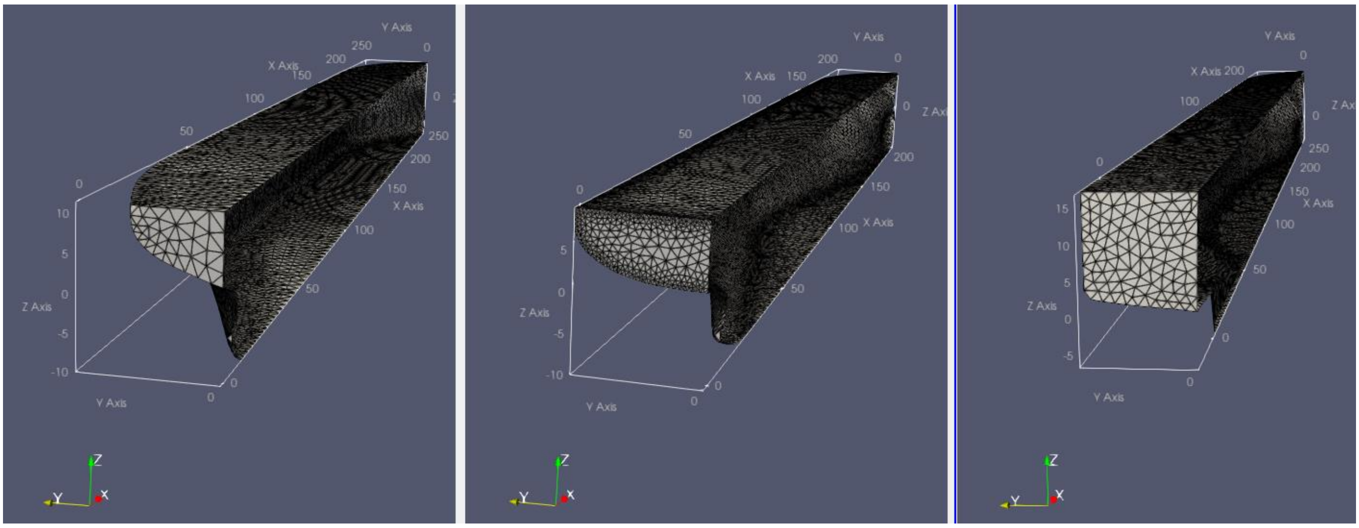

Figure 22 *Hull grids of the three vessels used in the study, i.e., bulk carrier (left), container vessel (center), and cruise ship (right). From FORCE Technology's ship database.*

Table 6 *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 7 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 8 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 9 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 |