Assessment of Ship Maneuverability Capacities Depending on Environmental Conditions in Sheltered Waters

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Abstract. This paper addresses the increasing complexity of maritime traffic in port areas, where different vessels with different missions and technologies interact in a confined space. To improve safety and efficiency, the study proposes a parametric toolbox for assessing the manoeuvrability of large vessels based on vessel type, key parameters and environmental conditions such as wind and currents, modelled using CFD techniques. The approach extends traditional station-keeping polar plots to predict low-speed manoeuvring during port operations. The results demonstrate the ability of the toolbox to estimate vessel behaviour and suggest optimal navigation and steering commands for precise path following in confined waters.

Keywords: environmental disturbances · marine autonomous surface ship · port operations slow-speed manoeuvrability · CFD · motion control

1 Introduction

Globalization has significantly increased maritime transportation with larger vessels and growing fleet sizes. Over the past 20 years, global seaborne trade and total port throughput have more than doubled, leading to higher traffic density and congestion in several areas [1]. Ports are often required to manage this increased demand without a proportional expansion of infrastructure, resulting in delays and reduced efficiency. As a result, navigation and manoeuvring in port areas have become critical aspects to consider [2]. Numerous models have been developed to support port planning and risk assessment [3–5]. In particular, the evaluation of environmental forces acting on vessels is fundamental for assessing manoeuvrability under adverse conditions [6–9,12]. The main environmental actions affecting ships manoeuvring in harbours are due to wind and currents, as wave action can be considered negligible in sheltered waters. Wind forces act on the freeboard, while currents act on the hull. Wind is characterized by much higher speeds than water currents, but currents can interact directly with the

K. J. Spyrou and N. Themelis (Eds.): IMAM 2025, *Innovations in Sustainable Maritime Technology*, pp. 107–119, 2025.
https://doi.org/10.1007/978-3-032-01432-0_9

ship propulsion system. Both effects depend on the ship type, geometry, and loading condition. The main methodologies for systematically determining the ability of a generic vessel to withstand meteorological and marine forces have been analysed [16]. This analysis focused on the primary environmental forces affecting vessels in port areas, distinguishing between the entrance (the stretch of sea adjacent to but outside the port) and the interior of the port itself. In the present work, these methodologies are applied to a specific geographic area: the port of Augusta, Sicily, Italy. The main ship characteristics required for the assessment of manoeuvrability were retrieved from the Automatic Identification System (AIS) and integrated with information about the propulsion layout and steering system. The missing quantities of interest were estimated by means of parametric models based on Computational Fluid Dynamics (CFD) computations and literature data, considering a parent ship for the main ship types (tanker, bulk, passenger ship and container ship) scaled according to the dimensions of the actual vessel calling at the port of Augusta. It should be noted that if more precise data are available for a specific unit, these estimates can be refined and calibrated for the vessel of interest.

The method presented foresees four main steps:

- ship modelling;
- environmental forces evaluation (wind and current);
- steering system description in terms of forces;
- solution of the system of equations to determine the vessel equilibrium under maximum environmental loads using only its own steering system.

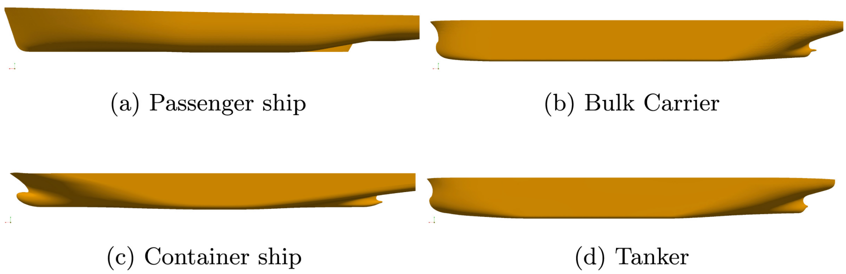
In the following paragraphs, each step is described in detail, and the results for a test case are presented.

2 Environmental Disturbances

The action of wind and current on the hull can generate significant forces due to the potentially high relative velocities between the fluid and the vessel, as well as the typically large surface area of the superstructure and the hull itself. Both effects depend on the relative speed between the fluid and the ship, the relative angle between the ship and the wind/current main direction and on the geometrical characteristics of the ship. Both the effects are studied using a Computational Fluid Dynamics (CFD) modelling to tune simplified regressions to be used in the model.

2.1 Current Forces and Moment

When a vessel moves with a generic uniform rectilinear motion relative to the sea, it generates a pressure field whose resultant can be represented as a force and a moment acting on the ship itself. The magnitude of these forces depends on the relative velocity of the fluid and the shape of the hull, including its wetted surface. This requires knowledge of the hull geometry or a good approximation thereof. Considering the vessel types relevant to this research, it was decided to use “standard” hull forms commonly employed in the marine field. Following an extensive literature review, the selected hull shapes are shown in Fig. 1. These hulls originate from model hulls commonly used for numerical and experimental benchmarking and are, therefore, well-suited to the objectives of this work. Four main categories have been identified: passenger and cargo ships, further divided into Bulk Carriers (parent hull is the *JBC*), Container Ships (parent hull is the *DTC*), and Tankers (parent hull is the *KVLCC*).


(a) Passenger ship

(b) Bulk Carrier

(c) Container ship

(d) Tanker

Fig. 1. Hull shapes for different kinds of vessels.

These hulls differ in the shapes of the bow and stern, as well as in their fineness coefficient. For each of these hull forms, at the corresponding design draft, a CFD analysis was performed to evaluate the forces generated when subjected to an incoming current. Using the open-source software OpenFOAM (version 4.1), multiple simulations were conducted adopting a domain as depicted in Fig. 2. The simulation setup consists of a parallelepiped-shaped domain aligned with the prevailing current direction (represented by the blue arrow in the figure) [23]. The domain dimensions were chosen to be sufficiently large to prevent interactions between the boundary conditions (domain boundaries) and the hull, thereby ensuring undisturbed external flow conditions. As a result, the computational domain was defined with dimensions of 5×2.5×1 times the ship length in length, width, and height, respectively. Within this domain, the hull was positioned and properly oriented by rotating it around the green axis (as shown in the figure) to achieve the required drift angle. Local refinement zones were introduced to better capture the disturbance generated by the hull itself, aligned with its motion (represented by the red box in the figure). This computational domain setup resulted in a simulation with approximately one million predominantly hexahedral cells. This setup follows the best practice reported in [13], where a mesh sensitivity analysis was conducted. No further details have been here reported for brevity. The presence of the free surface was modelled as a smooth, undeformable horizontal plane. While this simplification does not allow for the evaluation of wave formation generated by the hull, it remains a reasonable assumption for the considered low relative velocities, as in the present case, where the currents considered are only a few knots. This approach does not lead to significant

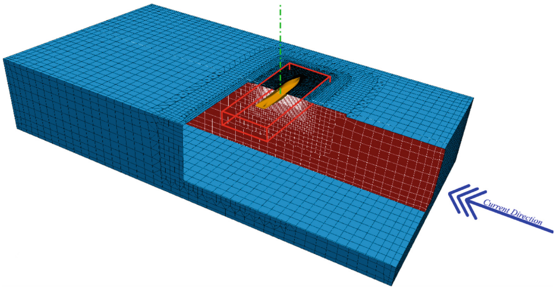
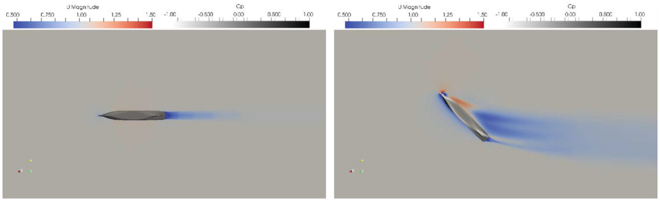
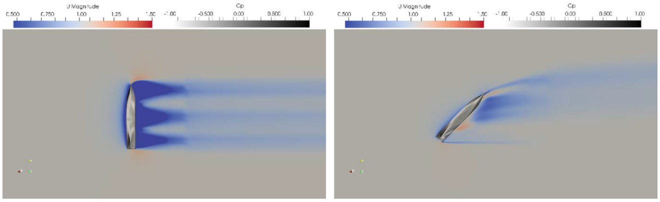


Fig. 2. Example of CFD computation with OpenFOAM.

information loss but greatly reduces computational time. For the sake of completeness, when a ship operates in sheltered waters, it could also operate in shallow water. This aspect becomes predominant only for quite small values of underwater keel clearance [13], which depend on the seabed bathymetry and the hull draft. Therefore, considering the statistical aim of the present activity and the selected study case, this effect has been neglected due to the complexity of having reliable values of actual ship draft. This assumption does not change the significance of the proposed approach. Figure 3, as an example, shows how the wake and pressure fields on the hull change with varying drift angles. It is evident that at 90°, the hull offers maximum resistance, generating a highly pronounced wake (blue areas represent reduced velocities). Figure 4 presents the dimensionless forces and moments (lines with markers) for all the hulls under investigation.



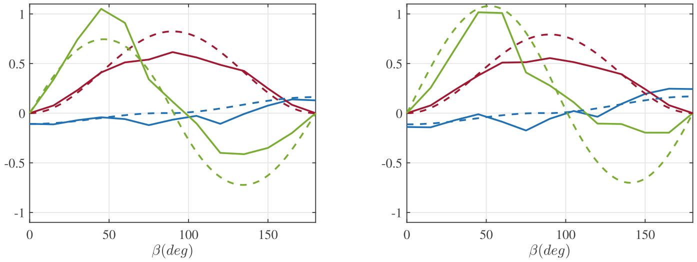
(a) 0° drift angle (b) 45° drift angle



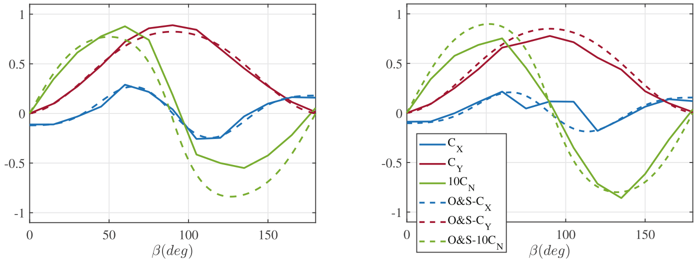
(c) 90° drift angle (d) 135° drift angle

Fig. 3. Example of flows validated via CFD approaches.

While the magnitudes of the forces are comparable, their trends vary depending on the specific hull geometries. As previously highlighted, to apply these data to hulls with different dimensional ratios, the trends were fitted using formulations proposed in the literature. After comparing the various available formulations, the approach proposed by [12, 22] was selected. This formulation ensures sufficient variability in the trends of forces and moments while maintaining physical consistency with the problem. Figure 4 presents a comparison between the CFD results and the calibrated formulation. It can be observed that, despite some negligible discrepancies—considered acceptable, particularly given the predominantly statistical nature of these analyses—the proposed formulation effectively captures the general trends. This makes the method suitable for application to ships with dimensional ratios different from those of the model ship.



(a) Container ship (b) Passenger ship



(c) Bulk carrier (d) Tanker ship

Fig. 4. Current forces and moment coefficients evaluated via CFD versus proposed method.

2.2 Wind Forces and Moment

When a structure is exposed to wind, it generates a force field whose resultant can be decomposed into a single force and a moment acting on the structure itself. Ships, in particular, are large structures that operate in areas frequently affected by significant winds. For this reason, assessing wind forces is of primary importance to ensure safety during port operations. To determine the effects of wind, it is necessary to know the shape of the above-water hull, including superstructure and exposed deck areas. However, due to the statistical nature of this study, it is not possible to define these shapes precisely in advance. Therefore, following the same approach adopted for current-induced forces, several representative models have been developed to cover the range of possible superstructure configurations for the hulls of investigation. One of the most significant parameters for determining the extent of the superstructure is undoubtedly their height. This can be estimated based on the visibility requirements imposed by IMO SOLAS [14], which provide an estimate of the superstructure height (H_{SPST}) as follows:

$$H_{SPST} = (\frac{0.85\, L_{WL}}{L_{vis}})(D - T_M + H_{DK}) + H_{DK} + 1.5 \tag{1}$$

where L_{WL} is the waterline length, $L_{vis} \in \{2\, L_{PP}, 500\,\mathrm{m}\}$ is the sight length, D is the vessel height, T_M is the mean draft, and H_{DK} is the height of the main bridge. Based on these data, superstructure shapes were generated to align with expectations. Figure 5 shows the five selected configurations.

(a) Case 0 (b) Case 1

(c) Case 2 (d) Case 3

(e) Case 4 (f) Case 5

Fig. 5. General shapes adopted for superstructures.

These configurations are characterized as follows: Fig. 5a absence of superstructures, used as a reference case; Fig. 5b-c presence of a single aft or forward deckhouse with a clear deck, representative of empty container ships or tankers; Fig. 5d aft deckhouse with container stacks, representing a fully loaded container ship; Fig. 5e a continuous superstructure extending from bow to stern, typical of cruise ships or passenger ferries; and Fig. 5f a forward deckhouse limited to the bow area, characteristic of hulls such as supply vessels. These configurations represent the main superstructure types, with minor exceptions deliberately neglected for the sake of simplicity and generality. Following the definition of the superstructure shapes, a CFD analysis was conducted using the previously described methodology. The numerical setup remained largely unchanged, with meshes of approximately one million elements. However, due to the less streamlined geometries, the resulting flow was more unstable, requiring a time-dependent solution and longer simulation times. Figure 6 illustrates a sample configuration used for wind force and moment estimation. This setup follows the main findings shown in [24], where a deeper validation was reported. Figure 7 shows the flow behaviour for two wind encounter angles. The effect of the presence of the hull on the surrounding air velocities is clearly evident.

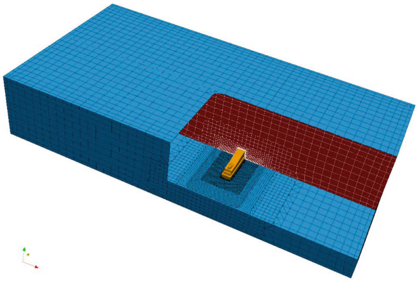
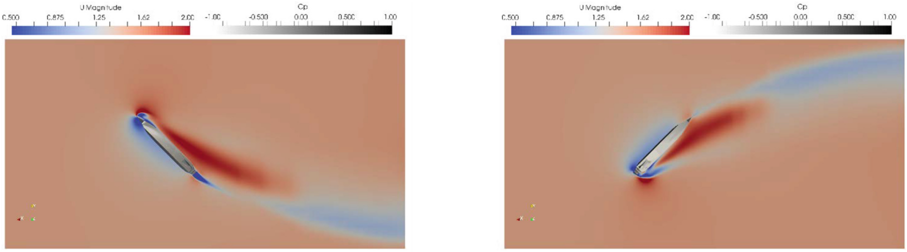


Fig. 6. Example of meshes for wind estimation with OpenFOAM.

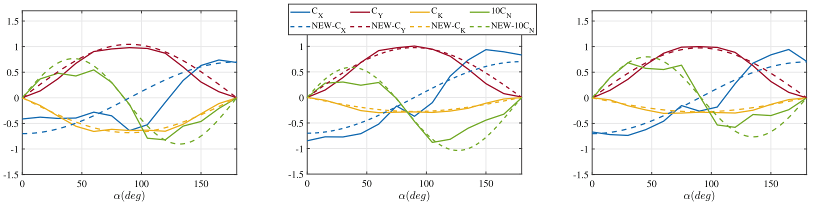


(a) 315°

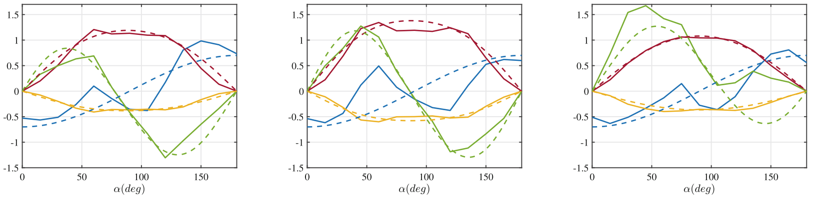
(b) 45°

Fig. 7. CFD simulation of wind flow for two different incoming directions.

Unlike the previous case, these force values—although non-dimensional with respect to exposed areas—show markedly different trends due to the significant geometric variations. Analytical models from the literature were also considered, leading to the development of a new methodology based on [9], which better fits the CFD data. Calibration details are omitted for brevity. Figure 8 shows a point-by-point comparison between the proposed formulation (dashed curves) and CFD results. The new model accurately captures forces and moments, with some deviations, especially in the longitudinal component, which remains several



(a) Case 0 (b) Case 1 (c) Case 2



(d) Case 3 (e) Case 4 (f) Case 5

Fig. 8. Comparison between the CFD calculations (continuous curves) and proposed method (dashed curves) of the dimensionless wind forces and moments in a range from 0° to 180° drift angle.

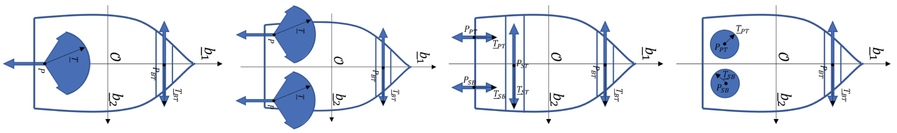
orders of magnitude smaller than the lateral one. Given the statistical nature of these models, the agreement is considered more than adequate for the scope of this study.

3 Allocation Model

The proposed model analyses the maximum conditions a vessel can withstand under environmental forces using its own steering systems. This requires accurate knowledge of both external forces and those generated by the ship. The analysis is typically conducted in a ship-fixed reference frame (see Fig. 9), centred at $L_{PP}/2$ on the symmetry plane. In harbour manoeuvring, the primary control systems are the bow thrusters and the main propellers coupled with rudders. The forces they produce depend mainly on the type of equipment and the installed power. Once the force trends for a given configuration are known, the vessel equilibrium must be solved as:

$$\begin{cases} \underline{F}_{env} + \underline{F}_{del} = 0 \\ \underline{N}_{env} + \underline{N}_{del} = 0 \end{cases} \tag{2}$$

where $\underline{F}_{env} = X_{env}\,\underline{b}_1 + Y_{env}\,\underline{b}_2$ is the environmental action resultant, $\underline{N}_{env} = N_{env}\,\underline{b}_3$ is the environmental resulting moment. The proposed system is based on a 3-DOF approach w.r.t. $\{\mathcal{O}, \underline{b}_1, \underline{b}_2, \underline{b}_3\}$-basis. Such relation allows computing, at each instant, the necessary resulting thrusts that each thruster is required to guarantee equilibrium. Indeed, $\underline{F}_{del} = \sum_i \underline{T}_i$ and $\underline{N}_{del} = \sum_i (P_i - \mathcal{O}) \wedge \underline{T}_i$ are the resultants of forces and moment, respectively, delivered by propulsion. In particular, $\underline{T}_i = X_i\,\underline{b}_1 + Y_i\,\underline{b}_2$ with $T_i \in [0, T_i^{max}]$ is the thrust vector of each thruster and $\underline{N}_i = N_i\,\underline{b}_3$ is the resulting moment of each actuator.



(a) Case (i)) (b) Case (ii) (c) Case (iii) (d) Case (iv)

Fig. 9. Selected vessel propulsion configurations.

Once the values of wind and current forces are known, by inverting (2), it is possible to evaluate the thrusts required from each actuator to meet the operational requirements, [17]. The four types of propulsion layout defined in the preliminary phase cover a wide range of the possible configurations for the vessels under study, see Fig. 9. However, whenever specific data on individual vessels are available, a more detailed performance assessment can be carried out. For each propulsion configuration, a specific algorithm has been implemented in order to solve the system. The considered configurations are: (i) single-screw or twin-screw ships with coupled propellers and rudders and a bow thruster Fig. 9a (general cargo, tanker and container ships); (ii) twin-screw ships with decoupled propellers and rudders and bow thruster Fig. 9b (Ro-Ro/pax and ferries); (iii) twin-screw ships with bow and stern thruster Fig. 9c (stern thrusters are installed on pax); (iv) twin-screw ships with azimuth main thrusters and a bow tunnel thruster Fig. 9d (cruise ships and work vessels). For the sake of brevity, it is not possible to show all detailed allocation algorithms. In general, solutions of (2) have been implemented in accordance with

$$\min_{x} \sum_{i} {T_i^{max}}^2 \tag{3a}$$

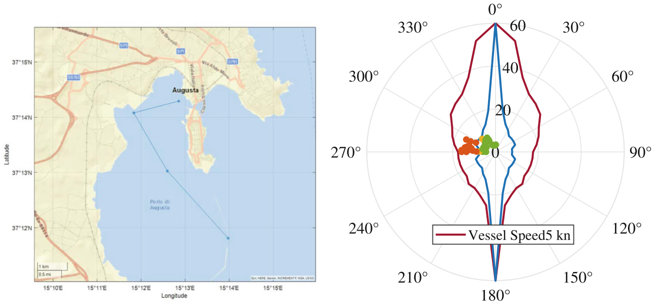
subject to:

$$\begin{cases} X_{env} + \sum_i X_i = 0 \\ Y_{env} + \sum_i Y_i = 0 \\ N_{env} + \sum_i \left(x_i\,Y_i - y_i\,X_i\right) = 0 \end{cases} \tag{3b}$$

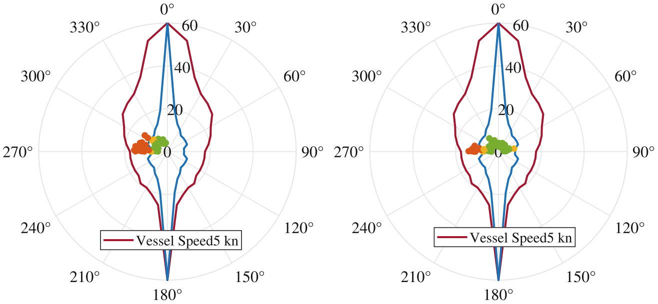
where x is the vector of the required actuations, which is unknown. The proposed formulation is the most general one, allowing the problem to be solved whenever the vessel is overactuated. Generally, for commercial vessels (2) can be solved directly due to the small number of propellers involved. In order to evaluate maximum allowable forces for each generic vessel, available data from the AIS have been adopted. In particular, it is possible to evaluate the AIS code that corresponds to a specific vessel type, the vessel main size, and vessel kinematics. Unfortunately, no data related to the propulsion system is currently available. Such data are essential for defining the vessel ability to withstand certain environmental disturbances. Therefore, to assess the available thrust, the methodologies proposed by the regulations for evaluating the performance of units in dynamic positioning applications have been used [10,17]. These formulations are specifically designed for dynamic positioning applications, making them particularly suitable for this study, which focuses on assessing manoeuvring performance in narrow waters and at low speeds. The models required some specific data such as brake power, propeller diameter, vessel length, and propulsion layout. Without specific vessel data, regressions have been used [18] regarding the propulsion power available on board container ships, bulk carriers, and tankers. Differently, specific relationships have been identified for Ro-Ro vessels and passenger ships based on the data available in the register books.

4 Results

Thanks to the available AIS data, a test was performed on the ship extracted from the route analysis, following the procedure proposed in [19]. In particular,



(a) Vessel Path (b) Path 1



(c) Path 2 (d) Path 3

Fig. 10. Sheltered waters navigation performances.

the approach path to the quay within the port of Augusta was considered, as shown in Fig. 10a. The route was divided into three straight segments, representing the most probable path based on ship traffic density. These three route segments define three ship heading angles, which are combined with the wind direction to determine the relative incidence angles with respect to the ship's bow [15]. Figure 10 shows an example of the expected results. The polar plots report wind speed in knots along the radial direction and wind incoming direction along the angular direction. In these simulations, it is assumed that the vessel proceeds along the three paths at a speed of 5 knots. The blue curve represents the maximum wind speed that the vessel is able to counteract with its actuators, under the assumption of degraded performance of the bow thrusters during forward motion. The red curve, instead, represents the wind limits sustainable when the bow thrusters are fully operational. The data points indicate the recorded weather conditions obtained from a historical database previously used in [20,21]. In particular, three colours are assigned to the real environmental conditions: green indicates wind speeds lower than 80% of the maximum and is considered safe even in the presence of degraded thruster performance; yellow corresponds to wind speeds between 80% and 100% of the maximum; red refers to environmental conditions for which assisted manoeuvring is required.

5 Conclusions

This paper presents a methodology for integrating advanced simulation models of low-speed ship manoeuvring capabilities with control algorithms that estimate the required actuation to ensure safe navigation under varying environmental conditions. The results obtained are suitable for integration into navigation support systems in seaports. Their reliability increases with the number of known parameters related to the vessels under consideration. The core design concept is to enable the management of ships approaching port waters, allowing for route planning within the port based on the vessel's propulsion configuration and marine weather conditions—for example, by assessing the need for support vessels (i.e., tugs). The models will be extended to include yaw motion modeling, enabling analysis of manoeuvring capabilities between waypoints. Further work is also underway to integrate the combined performance of manoeuvres involving tug assistance, shallow water effects, and bank suction.

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