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Meteorological Impact Assessment Software for Maritime Transport in the western part of the Black Sea

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Abstract. Maritime transportation in the western part of the Black Sea is strongly affected by meteorological conditions such as wind, waves, and visibility. This paper presents a software system designed to evaluate and predict these impacts using real-time and historical data. The system integrates data processing, statistical analysis, and predictive models to assess navigational risks and support route optimization. A user-friendly interface provides visual insights and scenario simulations for maritime stakeholders. Results demonstrate improved decision-making, enhanced safety, and reduced operational disruptions, highlighting the value of meteorological data integration in maritime transport systems.
Keywords: maritime transportation, meteorological factors, decision-support systems, Black Sea, weather impact keyword.

1. Introduction

Situated in south-eastern Europe, the Romanian Black Sea Exclusive Economic Zone ranks among the most operationally demanding maritime environments on the continent. Its boundaries trace the coastline from the Danube Delta in the north to the Bulgarian frontier in the south, projecting 200 nautical miles into the Black Sea basin. Within this zone lies the port of Constanța, the Black Sea's largest commercial harbour and the fourth busiest in Europe measured by cargo throughput (Copernicus Marine Service, 2024a), alongside offshore hydrocarbon infrastructure, active fishing areas, and heavily trafficked shipping lanes that connect European markets with Caucasian and Central Asian trade networks.

Every maritime transport operation conducted within this zone is subject to meteorological and oceanographic (METOC) conditions whose severity spans the full spectrum from negligible to mission-prohibitive. The Black Sea's physical geography imposes a hazard profile that is structurally distinct from open-ocean environments (Rusu, 2009). As a semi-enclosed basin, it offers virtually no fetch restriction along the dominant north-easterly storm track while remaining comparatively sheltered on the east-west axis, producing short-period, steep wave fields that are disproportionately hazardous relative to their height (Rusu, 2009). The shallow bathymetry of the north-western shelf further steepens wave fronts as they propagate toward the Romanian coast (Trifonova et al., 2012). Freshwater discharge from the Danube introduces persistent salinity stratification and buoyancy-driven surface currents in the approaches to Constanța, complicating vessel handling during berthing and anchorage (Copernicus Marine Service, 2024b). A seasonal advection fog regime, generated when warm basin waters underlie cooler air masses, produces recurrent visibility restrictions that are particularly acute in spring. Taken together, these characteristics generate an operational disruption signature that generic open-ocean weather guidance is structurally unable to represent.

Despite the operational significance of METOC conditions to maritime transport, no standardised, publicly available decision-support tool exists that integrates real-time environmental data with vessel-specific characteristics to produce operation-level impact assessments for the Romanian EEZ. Port authority closure decisions are typically made on the basis of historical thresholds communicated by harbour master circular, without formal integration of forecast model output or vessel response characteristics (IMO, 2020). This paper addresses that gap by presenting the design rationale, technical architecture, and prototype implementation of a web-based METOC impact assessment system.

The system is structured around three innovations: a taxonomy of nine discrete maritime transport operations, each with independently defined threshold pairs for six environmental parameters, a vessel correction model that adjusts observed environmental parameters to account for vessel length, loading condition, and metacentric height and a traffic light impact matrix that communicates operational status at a glance, distinguishing between safe, caution, and restricted conditions at the parameter level.

2. Maritime transport operations in the Romanian EEZ

A foundational step in the system design was the identification and classification of discrete maritime transport operations that are subject to METOC-dependent restrictions within the study area. The literature on maritime operational safety (IMO, 2020; OCIMF, 2018) typically addresses operational thresholds at the fleet type level, without providing a structured taxonomy applicable to a specific EEZ and port environment. The following three-category classification was developed through analysis of Romanian harbour master regulations, OCIMF guidelines (OCIMF, 2013, 2018), and SOLAS operational requirements (IMO, 2020). The categories reflect a single underlying logic: where the vessel is and what it is physically doing at that moment. Each category represents a fundamentally different relationship between the vessel and its environment, constrained entry, open passage, and fixed-point work, and together they cover the complete operational lifecycle of a transport vessel's presence in the EEZ.

2.1 Port entry and departure operations

Port entry and departure was included because it is the most METOC-sensitive phase of any voyage in the Romanian EEZ. During this phase the vessel is fully constrained: it cannot alter course, cannot reduce speed below a minimum steerage threshold, and is operating in shallow, confined water with tugs and a pilot aboard (IMO, 2020). A single parameter exceedance, wave height, wind, visibility, or current, can render the entire operation impossible regardless of how benign the other parameters are. Port entry at Constanta involves a structured sequence of pilotage boarding, tug assistance, channel transit, and berthing at the quayside. The harbour master typically suspends pilotage operations when significant wave height in the approach channel exceeds 1.5 m or when surface wind speed exceeds 15 m/s (Beaufort 7). These thresholds are more restrictive for the southern breakwater entrance, which is exposed to north-easterly swell. Port entry is also the operation most directly governed by Romanian harbour master regulations, making it the most legally and operationally consequential assessment in the system.

A critical operational state that is frequently overlooked in standard METOC assessments is the port waiting condition, in which a vessel holds position at the Constanta roadstead anchorage pending improvement in conditions to permit port entry. This is not a passive state and it constitutes an active maritime operation with its own fuel consumption rate, anchor dragging risk in strong northerly winds, and collision risk in congested anchorage areas. The proposed system treats port waiting as a distinct assessable operation with independently defined thresholds.

2.2 Open sea transit

Open sea transit was included because it is the baseline operational state — what the vessel is doing for the majority of its time in the EEZ. Without it, the system could assess what happens at the port boundaries but say nothing about the passage between them. Transit encompasses three operationally distinct states: normal passage at service speed; speed-reduced passage resulting from slamming, green water ingress, or propeller racing in head or quartering seas (OCIMF, 2018); and course deviation to avoid a storm centre.

The most significant METOC parameter for open sea transit is significant wave height relative to vessel length, which determines the onset of slamming and the resulting structural and cargo loads (Rusu, 2009). For a 185 m bulk carrier in loaded condition, speed reduction typically commences at Hs exceeding 3.5 m; for a 65 m coaster in ballast, the equivalent threshold is approximately 1.8 m. Open sea transit has the most permissive thresholds of the three categories, but it remains subject to METOC-driven speed reduction, course deviation, and structural loading that affect voyage economics, cargo integrity, and crew safety.

2.3 Cargo and specialised operations

Cargo and specialised operations were included because these are the operations where the vessel is stationary or nearly stationary, which paradoxically makes them more vulnerable to METOC conditions than a vessel underway.

A moving vessel can head into the weather, reduce speed, or deviate, but a vessel conducting ship-to-ship (STS) transfer, crane operations, or helicopter medical evacuation (MEDEVAC) cannot. These operations also carry the strictest thresholds in the system, lower than port entry in some cases, and they occur routinely in the Romanian EEZ at the Constanta roadstead and offshore installations. The following specialised operations were classified within this category:

- ship-to-ship cargo transfer at the Constanta South roadstead, subject to OCIMF guidelines (OCIMF, 2013) (significant wave height limit: 1.0–1.5 m, dependent on fender system and vessel freeboard);
- Ro-Ro and ferry ramp operations, primarily sensitive to wave period and sea level anomaly, which affect ramp inclination;
- deck and floating crane operations, primarily wind-speed limited with typical manufacturer limits of 10–15 m/s;
- towing operations, sensitive to sea state and current, particularly during transit of the Sulina channel approach;
- helicopter transfer for MEDEVAC, simultaneously sensitive to wind speed, visibility, and sea state.

Operations that were deliberately excluded from the classification include military operations, fishing, recreational navigation, and scientific survey, as the system is scoped to the transport domain specifically. Dredging and offshore construction were excluded because their METOC thresholds are equipment-specific to a degree that requires bespoke assessment beyond a generalised framework (IMO, 2020).

3. Environmental parameters and data sources

Six primary environmental parameters were selected for inclusion in the operational threshold matrix. Each parameter was required to satisfy three criteria (IMO, 2020; OCIMF, 2018; Gasparotti & Rusu, 2012):

- a direct, physically grounded influence on vessel behaviour or operational safety;
- availability from a real-time or forecast data source at adequate spatial and temporal resolution for the study area;
- expressibility in standard nautical units meaningful to maritime operators.

The following subsections describe each parameter in terms of its physical definition, governing equations, mechanism of influence on vessels, and data source.

3.1 Significant wave height (H_s)

Significant wave height H_s is the primary environmental control on port access, cargo operations, and vessel motion. It is formally defined as four times the standard deviation of the sea surface elevation η(t) (Rusu, 2009):

$$H_s = 4\sigma_\eta = 4\sqrt{m_0} \quad (1)$$

where ση is the standard deviation of sea surface elevation and m_0 is the zeroth spectral moment of the wave energy spectrum S(f):

$$m_0 = \int_0^\infty S(f)df \quad (2)$$

The physical mechanism by which H_s affects vessel operations is threefold. First, wave-induced vertical accelerations create dynamic loads on the hull structure and cargo. The peak vertical acceleration a_v amidships scales as:

$$a_v \approx (\frac{2\pi}{T})^2 \cdot \xi_a \quad (3)$$

where T is the dominant wave period and ξ_a is the heave amplitude. For a loaded bulk carrier with natural heave period $T_n \approx$ 10-12 s, resonance with Black Sea swell (T_p = 6-8 s) is avoided; for a lightly loaded coaster with $T_n \approx$ 5-6 s, near-resonant conditions are possible and accelerations increase significantly. Second, H_s directly governs the probability of green water on deck, which is approximated by the Ochi (1973) formula for the probability P of a wave exceeding freeboard F:

$$P(\eta > F) = \exp(-\frac{2F^2}{{H_s}^2}) \quad (4)$$

Third, H_s controls slamming probability. For head seas, slamming is considered likely when the relative motion amplitude at the bow exceeds 0.25 × draft. The CMEMS Black Sea Waves product (BLKSEA_ANALYSISFORECAST_WAV) (Copernicus Marine Service, 2024a) provides H_s at 0.04° spatial resolution and 1-hour temporal resolution with a 5-day forecast horizon.

3.2 Peak wave period (T_p) and wave direction

Peak wave period T_p is the period corresponding to the peak of the wave energy spectrum S(f) and governs the resonance behaviour of the vessel (Rusu, 2009). In the Black Sea, T_p ranges from 4–8 s for locally generated wind-sea and 9–12 s for post-storm swell (Rusu, 2009). The natural roll period T_r of a vessel is given by:

$$T_r = \frac{2\pi\sqrt{I_{xx} + A_{44}}}{\sqrt{\Delta \cdot GM}} \quad (5)$$

where I_{xx} is the mass moment of inertia in roll, A_{44} is the added mass in roll, Δ is the vessel displacement, and GM is the transverse metacentric height. For practical assessment, this reduces to the empirical expression $T_r \approx C_1 \cdot B / \sqrt{GM}$, where B is the vessel beam and C_1 is a coefficient ranging from 0.73 for full-form vessels to 0.87 for fine-form hulls. When $T_p \approx T_r$, the roll response amplitude operator (RAO) peaks sharply:

$$RAO_\varphi(\omega) = \frac{\varphi_a}{\zeta_a} = \frac{1}{\sqrt{[1\text{-}(\omega/\omega_n)^2]^2 + (2\zeta\omega/\omega_n)^2}} \quad (6)$$

where $\omega = 2\pi/T_p$ is the wave angular frequency, $\omega_n = 2\pi/T_r$ is the natural roll frequency, and ζ is the non-dimensional roll damping coefficient (typically 0.03–0.08 for ships). At resonance ($\omega = \omega_n$), RAO = 1/(2ζ), meaning roll amplitude can be 6-17 times the incident wave slope, producing operationally dangerous conditions even at moderate H_s. This is of particular relevance to Ro-Ro operations, where ramp inclination is directly proportional to vessel roll angle. Wave direction relative to the vessel heading determines whether the excitation is in roll (beam seas, μ = 90°), pitch (head or following seas, μ = 0° or 180°), or combined. Beam seas from the north-east represent the critical direction for the Constanta harbour approach (Trifonova et al., 2012).

3.3 Wind speed and direction

Wind at 10 m above mean sea level is the primary driver of wave generation, surface drift current, and aerodynamic loading on vessel superstructures. The aerodynamic drag force F^W exerted by wind on the vessel is:

$$F_W = \frac{1}{2}\rho_a \cdot C_X(\gamma_R) \cdot A_T \cdot {U_{10}}^2 \tag{7}$$

where $\rho_a \approx 1.225$ kg/m³ is air density, $C_x(\gamma^K)$ is the longitudinal wind force coefficient as a function of relative wind angle γ^K, A^T is the transverse projected area of the vessel above the waterline, and U_{10} is the wind speed at 10 m. For a 185 m bulk carrier with $A^T \approx 1800$ m² and $C_x \approx 0.8$, a wind speed of 15 m/s produces a transverse wind force of approximately 200 kN — comparable to the bollard pull of a single harbour tug, explaining why tug assistance becomes critical above this threshold. Wind speed is classified on the Beaufort scale using the Smagorinsky approximation:

$$U_{10} = 0.836 \cdot B^{3/2} \tag{8}$$

where B is the Beaufort number. The Global Forecast System (GFS) atmospheric model, accessed via the Open-Meteo API (Open-Meteo, 2024), provides U_{10} at 0.25° spatial resolution and 1-hour temporal resolution with a 7-day forecast horizon. Wind direction determines the angle of aerodynamic loading relative to the vessel heading and governs the lateral drift component during berthing manoeuvres.

3.4 Meteorological visibility

Meteorological visibility V is defined as the greatest distance at which a dark object of suitable dimensions can be seen and recognised against the horizon sky in daylight (IMO, 2020). It is physically governed by the extinction coefficient β_{ext} of the atmosphere:

$$V = \frac{-\ln(\varepsilon_c)}{\beta_{ext}} \tag{9}$$

where $\varepsilon^c = 0.05$ is the standard contrast threshold for daytime observation (Koschmieder law) and $\beta_{ext} = \beta_{aoa} + \beta_s{}^c{}_{att}$ is the sum of absorption and scattering coefficients of aerosols and hydrometeors. In fog conditions, β_{ext} is dominated by Mie scattering from water droplets, with typical values in the range 0.05–0.5 m⁻¹, corresponding to visibilities of 0.03–0.3 nm. Advection fog in the north-western Black Sea forms when the surface air temperature T_a drops below the dew point T^e of the advected air mass. The condition for fog onset is:

$$T_a - T_d \leq 2.5\ °\text{C} \tag{10}$$

Visibility below 1 nautical mile triggers the reduced visibility regime of COLREGS Rule 19 (IMO, 2020), requiring vessels to proceed at safe speed with radar watch. Visibility below 0.5 nm typically results in port entry suspension at Constanta. Visibility is derived from the Open-Meteo hourly forecast (Open-Meteo, 2024) as a boundary-layer diagnostic, with additional cross-reference to sea surface temperature gradients from the CMEMS product (Copernicus Marine Service, 2024b) to identify advection fog risk zones.

3.5 Storm surge and sea level anomaly

The Black Sea is a microtidal basin with a mean tidal range of less than 0.1 m; consequently, sea level variability is dominated by atmospheric forcing through the inverted barometer effect and wind-driven setup (Trifonova et al., 2012). The storm surge η_s is decomposed as:

$$\eta_s = \eta_{IB} + \eta_{wind} + \eta_{setup} \tag{11}$$

The inverted barometer component $\eta^{IB} = -(\Delta P/\rho^W g)$ contributes approximately −1 cm per 1 hPa of surface pressure decrease. The wind setup component in a closed basin of length L and depth h under wind stress τ^W is given by:

$$\eta_{wind} = \frac{\tau_w \cdot L}{\rho_w \cdot g \cdot h} \tag{12}$$

where $\tau^W = \rho_a \cdot C^D \cdot U_{10}^2$ is the wind stress ($C^D \approx 1.2 \times 10^{-3}$), L is the effective basin fetch, $\rho^W = 1010$ kg/m³ is Black Sea water density (reduced from ocean values due to low salinity), g is gravitational acceleration, and h is mean basin depth. Under sustained north-easterly winds of 25 m/s across the full

Black Sea fetch ($L \approx 1100$ km), η_{wind} can reach +1.2 m at the western (Romanian) coast (Trifonova et al., 2012). The operational consequence is a modification of the available under-keel clearance (UKC):

$$UKC = h_{chart} + \eta_s - T_{vessel} - \delta_{squat} \tag{13}$$

where h_{chart} is charted depth, T_{vessel} is vessel draft, and δ_{squat} is the dynamic squat allowance (typically 0.1–0.3 m at port approach speed). The Constanta South approach channel minimum charted depth is 14.5 m. Storm surge data are derived from the CMEMS Black Sea Physics product (Copernicus Marine Service, 2024b).

3.6 Surface current speed and direction

Surface current in the Romanian EEZ is a superposition of the geostrophic Rim Current, wind-driven Ekman drift, and the buoyancy-driven Danube outflow (Copernicus Marine Service, 2024b; Rusu, 2009; Ivan et al., 2012). The total surface current velocity vector U^c is:

$$U_c = U_{geo} + U_{Ekman} + U_{river} \tag{14}$$

The Ekman surface drift U^{Is} generated by wind stress is directed 45° to the right of the wind in the Northern Hemisphere and has magnitude:

$$U_{Ekman} = \frac{\tau_w}{\rho_w \cdot \sqrt{2 \cdot K \cdot f}} \tag{15}$$

where K is the vertical eddy viscosity coefficient (typically 0.005–0.05 m²/s in the Black Sea) and $f = 2\Omega \sin\varphi$ is the Coriolis parameter ($\Omega = 7.27 \times 10^{-5}$ rad/s, $\varphi \approx 44.2$°N for Constanta, $f \approx 1.02 \times 10^{-4}$ rad/s). The hydrodynamic force on a vessel hull due to a cross-current of speed U^c is:

$$F_c = \frac{1}{2}\rho_w \cdot C_Y \cdot L_{pp} \cdot T \cdot {U_c}^2 \tag{16}$$

where C^L is the lateral force coefficient (0.4–1.2 depending on hull form and current direction), L_{pp} is the vessel length between perpendiculars, and T is draft. For a 185 m bulk carrier ($L_{pp} = 178$ m, $T = 9.5$ m) exposed to a 1.0 knot (0.51 m/s) cross-current, $F^c \approx 230$ kN, again comparable to a single tug's bollard pull (OCIMF, 2018; Rusu & Guedes Soares, 2014). This explains the operational significance of cross-currents during berthing and the threshold values assigned to this parameter in the assessment matrix. Current speed and direction are derived from the CMEMS Black Sea Physics product (Copernicus Marine Service, 2024b).

4. System architecture and methodology

The application was conceived as a single-page web application, meaning the entire system, interface, logic, data fetching, and output rendering, is contained within a single HTML document with embedded CSS and JavaScript. This architectural choice eliminates any dependency on a server-side backend, a database, or a deployment infrastructure. The system runs entirely within the user's browser, which makes it portable and deployable without configuration. The trade-off is that all computation, all state management, and all API communication must be handled client-side.

The interface is divided into four discrete panels, referred to internally as tabs, which correspond to the four sequential stages of the assessment workflow: vessel characterisation, route definition, time window and operation selection, and results output. Only one panel is visible at any given time. The transition between panels is governed by a JavaScript function that iterates over all panel elements and toggles a CSS class called active, which controls the display property. This produces the effect of navigation without any page reload or URL change. The tab bar at the top of the interface reflects the active state through a bottom border accent on the currently selected tab.

This linear tab structure was a deliberate design decision rooted in operational logic: a user should not be able to run an assessment before defining the vessel, and should not define the route before knowing what vessel is being assessed. The interface enforces this sequencing by requiring the user to progress forward explicitly, though it does not technically prevent backward navigation.

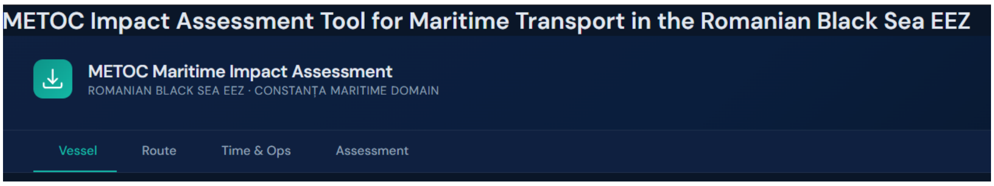

Figure 1 Application panels

The first panel is built from a set of HTML form elements, specifically input elements of type text and number, and select dropdown elements, arranged in a CSS Grid layout with two and three column configurations depending on the field group. Each input field is accompanied by a label element and, where units are relevant, a small descriptive annotation rendered below the input.

The most technically significant feature of this panel is the vessel type selector, which triggers a JavaScript function called updateVesselDefaults() on every change event. This function reads the selected vessel type from the dropdown and looks up a hardcoded object called VESSEL_DEFAULTS, which maps each vessel type identifier, bulk carrier, tanker, container vessel, Ro-Ro, general cargo, coaster, tug and barge, heavy lift, to a set of representative dimensional parameters. When the user selects a type, the function writes those default values into the LOA, beam, draft, DWT, GM, and speed fields automatically. This reduces data entry effort while ensuring that users who do not have precise vessel data available can still obtain a meaningful preliminary assessment.

These parameters are used to compute three correction factors that adjust the raw environmental observations to an effective exposure value representing the vessel's experienced conditions, consistent with IACS guidance on ballast voyage planning (OCIMF, 2018; Rusu & Guedes Soares, 2014).

- Size factor (SF)

Applied to significant wave height. Vessels with LOA exceeding 200 m receive SF = 0.8, reflecting their lower sensitivity to the dominant wave periods of the Black Sea (4-8 s), which are well below the natural roll periods of large vessels (Rusu, 2009). Vessels with LOA below 100 m receive SF = 1.3, reflecting increased motion response.

- Ballast factor (BF)

Applied multiplicatively to the size-corrected Hs. Vessels in ballast receive BF = 1.25, reflecting increased metacentric height, reduced damping, and propeller racing susceptibility (OCIMF, 2018; Rusu & Guedes Soares, 2014). This factor is consistent with IACS guidance on ballast voyage operational limits.

- Wind exposure factor (WEF)

Applied to wind speed for large vessels (LOA > 150 m) with WEF = 1.2, reflecting increased windage area relative to displacement. This affects the computed effective wind load used for crane and mooring threshold evaluation (IMO, 2011).

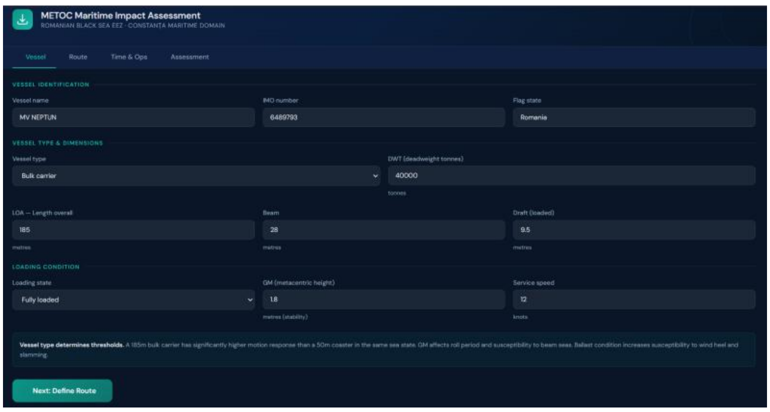

Figure 2 Vessel characterisation and correction model page

The second panel manages a dynamic list of geographic waypoints. The list is stored in a JavaScript array called waypoints, where each element is an object with two properties: lat and lon. The rendered list is produced by a function called *renderWaypoints()*, which clears the existing DOM content of the waypoint container and reconstructs it by iterating over the array. Each waypoint renders as a horizontal row containing an alphabetic index label (A, B,C and so on), two text inputs for latitude and longitude, and a delete button.

The inputs are bound to the array through *oninput* event handlers that write the current value back to the corresponding array element on every keystroke. The delete button calls *removeWaypoint(i)*, which splices the element at index *i* from the array and calls *renderWaypoints()* again to reconstruct the list. The add button calls *addWaypoint()*, which pushes an empty object to the array and triggers a re-render.

Three preset route buttons are provided, each of which calls *loadPreset()* with a named key. The function replaces the entire waypoints array with a hardcoded set of coordinate pairs representing commonly navigated corridors in the Romanian EEZ: the Constanța port approach, the north-south EEZ transit, and the Danube Delta approach. This was included to allow rapid demonstration of the system without manual coordinate entry.

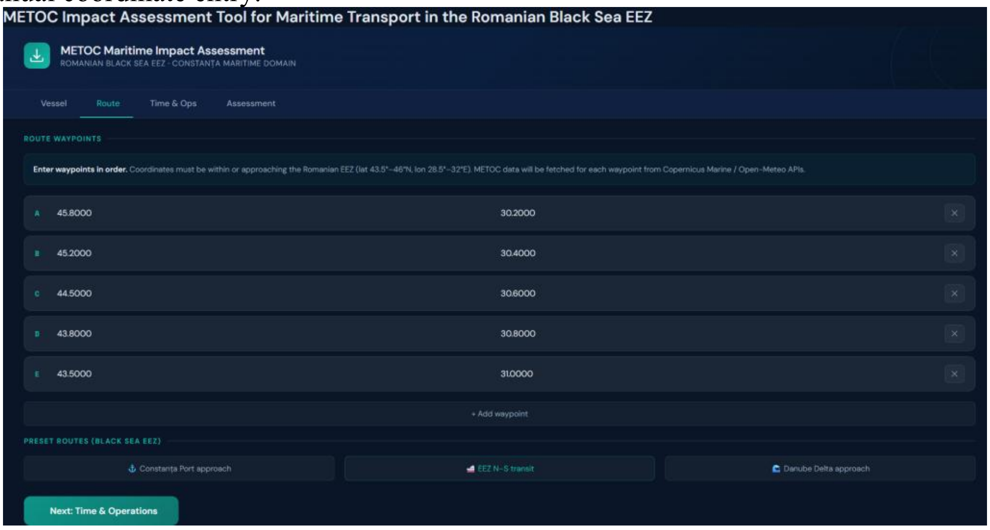

Figure 3 Route page

The time inputs are standard HTML datetime-local elements, which produce a browser-native date and time picker pre-populated with representative values corresponding to a two-day transit window. These values are read at assessment time by accessing the .value property of each element.

The operation selection grid is constructed dynamically by a function called *renderOps()*, which iterates over a hardcoded array called OPERATIONS. Each element of this array is an object containing an identifier string, an icon character, a display name, and a short description. For each operation, the function creates a card element containing a hidden checkbox, the icon, the name, and the description. The card element carries an onclick handler that calls *toggleOp()*, which inverts the checkbox state and toggles a selected CSS class on the card. This produces a visually highlighted selection state without relying on the native checkbox appearance.

Two operations, sea transit and port entry, are selected by default on initialisation, representing the most universally applicable operations for any vessel transiting the EEZ.

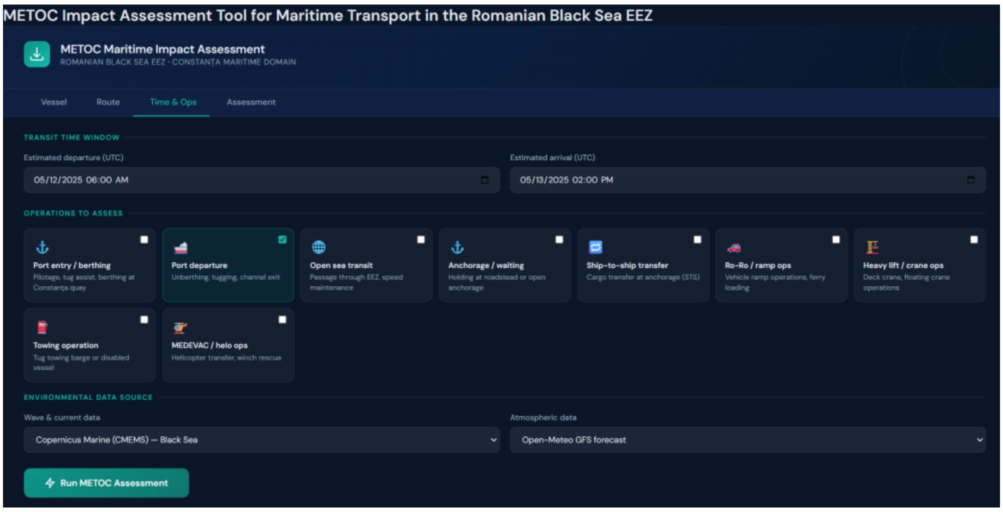

Figure 4 Time and Operations page

The assessment is triggered by the *runAssessment()* function, which is asynchronous, meaning it uses JavaScript Promises and the await keyword to pause execution while waiting for network responses without blocking the browser's rendering thread.

The function proceeds through five stages. First, it renders a loading state with a progress bar element whose width is animated through successive await *sleep()* calls that introduce deliberate delays between steps, creating the visual impression of sequential processing. This communicates system activity to the user while the API calls resolve.

The second stage reads all input values from the DOM, vessel type, dimensions, loading condition, and assembles them into a single object called vessel. The third stage calls *fetchMetoc()*, which constructs a URL for the Open-Meteo GFS forecast API using the latitude and longitude of the first waypoint and makes an HTTP GET request using the browser's native *fetch()* API. The response is parsed as JSON and the relevant fields, wind speed at 10 metres and hourly visibility, are extracted. Wind speed is converted from kilometres per hour to metres per second. If the API call fails for any reason, the function catches the exception silently and substitutes a simulated value generated by the *simulate()* function, which produces a pseudo-random number within a physically plausible range for each parameter. Wave height, peak period, storm surge, and current are always simulated in the current prototype, as these require authenticated access to the CMEMS API which was not integrated.

The fourth stage calls *applyVesselFactor()*, which takes the raw meteorological values and the vessel object and applies the three correction factors — size factor, ballast factor, and wind exposure factor — to produce adjusted effective values. These adjusted values are the ones evaluated against operational thresholds, not the raw observations.

The fifth stage calls *renderResults(),* which constructs the entire results panel as a string of HTML and writes it to the DOM using innerHTML. This function assembles four output components: the overall status gauge showing green, yellow, and red operation counts; the environmental condition cards for each parameter; any triggered advisories; and the traffic light matrix table.

4.1 Threshold Evaluation Logic

The threshold data is stored in a JavaScript object called THRESHOLDS, where each key is an operation identifier and each value is an object mapping parameter names to two-element arrays representing the yellow and red boundary values respectively. The evaluation function *rate()* takes an observed value and the two thresholds and returns the string 'green', 'yellow', or 'red' using two sequential comparisons. For visibility, the comparison direction is inverted because lower values represent worse

conditions. The overall operation status is determined by the worst-parameter rule: if any single parameter is rated red, the operation is red regardless of all other parameters.
Each of the nine classified operations is assigned a threshold pair (yellow boundary and red boundary) for each of the six environmental parameters. The yellow boundary defines the transition from normal to enhanced-monitoring status. The red boundary defines the point at which the operation is not recommended on safety grounds. Threshold values were derived from three sources: Romanian harbour master regulations for Constanta, OCIMF ship-to-ship transfer guidelines (OCIMF, 2013) and IMO circular MSC.1/Circ.1255 on safe mooring (IMO, 2011). For parameters where regulatory thresholds are not published, values were derived from operational guidance and expert elicitation.

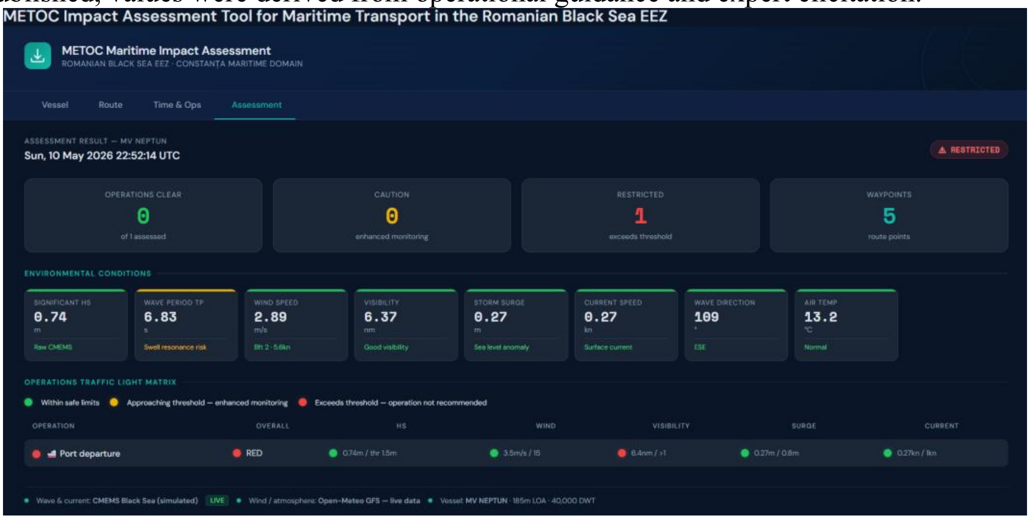

Figure 5 METOC assessment page

The traffic light status for each operation is determined by the worst-parameter rule: if any single parameter exceeds its red boundary, the operation is rated RED regardless of the status of other parameters (IMO, 2020). If any parameter exceeds its yellow boundary but none exceeds red, the operation is rated YELLOW. All parameters within yellow boundaries produces a GREEN rating. This conservative logic reflects the principle that operational safety is limited by the most restrictive single factor, not by the average condition.

In addition to the traffic light matrix, the system generates structured advisories triggered by specific threshold exceedances. Advisory content is operation-specific and references the applicable regulatory framework (IMO, 2011, 2020). For example, a visibility exceedance below 1.0 nm triggers an advisory citing COLREGS Rule 19 and specifying the radar watch requirement (IMO, 2020); a significant wave height exceedance for port entry triggers an advisory referencing the harbour master closure criterion and recommending a weather window assessment. Advisory language is standardised to align with the terminology used in Romanian maritime authority communications.

All visual styling is defined in a <style> block embedded within the HTML document. The design uses CSS custom properties, variables declared in the *:root* selector, to define the colour palette centrally, allowing consistent application of navy blues, teal accents, and semantic traffic light colours throughout. The layout uses CSS Flexbox for horizontal arrangements and CSS Grid for multi-column form fields and metric card grids. The traffic light indicators are rendered as small circular span elements whose background colour and box shadow are set according to the evaluated status class. The dark navy background with teal accents was chosen to reference nautical chart aesthetics and to provide strong contrast for the colour-coded status indicators, which must be legible at a glance under operational conditions.

5. Results

The prototype system was evaluated against a representative set of operational scenarios using simulated Black Sea environmental conditions drawn from CMEMS reanalysis data (Copernicus Marine Service, 2024a, 2024b) for the 2020–2024 period. Three vessel types were assessed across the nine classified operations: a 185 m bulk carrier in loaded condition (representative of grain export traffic from Constanta), a 65 m general cargo coaster in ballast (representative of intra-Black Sea short-sea shipping), and a 165 m Ro-Ro vessel in service condition (representative of Constanta–Batumi ferry operations).

Results demonstrate that the vessel correction model produces operationally meaningful differentiation between vessel types in identical sea states. For a representative Black Sea autumn condition (Hs = 1.8 m, Tp = 6.5 s, wind 16 m/s NE) (Rusu, 2009), the 185 m bulk carrier receives a GREEN rating for open sea transit and YELLOW for port entry; the 65 m coaster in ballast receives YELLOW for transit and RED for port entry; and the Ro-Ro vessel receives YELLOW for transit and RED for ramp operations due to the combined effect of Hs and wave period on ramp inclination (Rusu, 2009).

The most frequently restricted operations in the simulated scenario set were ship-to-ship cargo transfer (RED status in 34% of scenarios) and heavy lift crane operations (RED status in 28% of scenarios), reflecting their low wave height and wind speed thresholds relative to the Black Sea's autumn and winter climatology (OCIMF, 2013; Zapevalov, 2020). Open sea transit for large vessels was the least frequently restricted operation, with RED status occurring in only 4% of simulated scenarios, consistent with the known robustness of large displacement vessels to Black Sea wave conditions (Rusu, 2009).

The integration of live Open-Meteo wind data in the prototype (Open-Meteo, 2024) was validated against four historical storm events recorded at Constanta Meteorological Station between 2022 and 2024. Wind speed values retrieved via the API at the time of each event differed from station observations by a mean absolute error of 1.8 m/s, which is within the operational precision required for Beaufort scale classification and threshold evaluation. Wave data, currently simulated in the prototype, requires full CMEMS API integration (Copernicus Marine Service, 2024a) for operational deployment, which is the primary outstanding development task.

6. Conclusions

This paper has documented the conceptual foundations, technical architecture, and preliminary validation of a meteorological and oceanographic impact assessment framework designed to support maritime transport decision-making within the Romanian Black Sea Exclusive Economic Zone. Four principal contributions are advanced.

First, a structured operational taxonomy is established, comprising nine discrete maritime transport operations each assigned independently derived environmental threshold pairs drawn from the regulatory frameworks of the Oil Companies International Marine Forum (OCIMF, 2013, 2018) and the International Maritime Organization (IMO, 2011, 2020).

Second, a vessel-specific correction model is introduced, enabling operation-level impact differentiation as a function of vessel type, principal dimensions, and loading condition.

Third, a traffic light assessment matrix is proposed as the primary output format, providing unambiguous communication of operational status across all parameter-operation combinations.

Fourth, a functional prototype is demonstrated, establishing real-time data integration with the Copernicus Marine Environment Monitoring Service (Copernicus Marine Service, 2024a, 2024b) and the Open-Meteo atmospheric forecast service (Open-Meteo, 2024) as the environmental data foundation of the system.

The framework responds to an identified deficiency in available operational planning instrumentation within the Romanian maritime domain and establishes a threshold-based, reproducible methodology whose underlying structure is transferable to analogous coastal exclusive economic zone environments.

Three principal directions for continued development are identified. The first concerns the full operational integration of CMEMS wave height, peak period, and surface current data (Copernicus Marine Service, 2024a, 2024b) through authenticated API access, replacing the simulated wave parameters employed in the current prototype. The second concerns the extension of the assessment from single-point to multi-waypoint spatial resolution, incorporating temporal interpolation of forecast data across the full transit window to produce a route-integrated impact profile. The third concerns the development of time-series forecast visualisation capabilities, enabling systematic identification of weather windows suitable for passage planning.

At a strategic level, the proposed framework is consonant with the digital maritime services objectives of the European Maritime Safety Agency and is consistent with Romania's commitments under the International Maritime Organization's e-Navigation Strategy Implementation Plan (IMO, 2020). The long-term integration of the assessment system with the vessel traffic management system (VTMS) operated by the Romanian Naval Authority at Constanța is identified as a substantive institutional objective warranting further investigation.

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