VFWR: Charting the Optimal Voyage

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***Abstract*—Weather routing (WR) is a critical component of maritime operations, directly impacting fuel efficiency, voyage duration, and navigational safety. We present VFWR (VesselFront Weather Routing), an optimization framework for ship weather routing based on the A* path-finding algorithm with a weather-aware heuristic incorporating real-time forecast, wave height threshold, maximum latitude constraint, no-go areas, and minimization of the time spent within emission control area (ECA). To ensure accuracy based on the updated forecasts, re-routing is performed at six-hour intervals throughout the trip. VFWR is validated against a dataset of 100 historical voyages using hindcast weather data, while calculating optimized routes in a median of 23 seconds and consistently producing shorter distances and durations than real-world trips across all tested voyages, with a median trip duration of 46.92 hours based on telemetry data. These results highlight VFWR as an efficient, accurate, and practical tool for real-world maritime decision-making.**

***Index Terms*—weather routing, optimization, search space, safety, constraints.**

I. Introduction

In the maritime domain, weather routing (WR) concerns the prediction of the traversed route of a vessel considering meteorological forecasting [1]. The optimization goal based on which the calculation of the optimal route is conducted refers to minimizing one of the following: (1) the distance travelled, (2) the sailing time, and/or (3) fuel oil consumption (FOC) [2]. The goal of ship weather routing is to provide efficient and secure navigation [3]. From an economic perspective, the International Maritime Organization (IMO) has estimated that approximately 90% of global trade is facilitated by maritime transport [4]. In terms of environmental impact, transport operations conducted through maritime routes accounted for approximately 2.3% of global CO_2 emissions by 2023, as reported by the International Council on Clean Transportation (ICCT) [5]. These emissions, among other factors, led the IMO to revise its regulatory framework in alignment with the United Nations' (UN) sustainability goals, with the aim of achieving a 30% reduction in greenhouse gas emissions by 2030 and ultimately eliminating them by 2050 [6]. These figures emphasize the necessity of accurate and efficient WR solutions to support environmentally and economically responsible operational decision-making.

There are several requirements that a WR service must satisfy. First, path-finding algorithms in WR are contingent upon a discretized representation of the sailing sea, where the resolution of this mesh directly influences the quality of the solution obtained. Coarse grids may result in the under-representation of weather variability across long edges, thereby introducing inaccuracies in route cost estimation and path optimality [7]. Moreover, with a coarse grid on the coastlines, safety is compromised and the optimal path is subject to significant discrepancies due to the coastline topography, in conjunction with the grid resolution [8].

Second, WR must take into consideration user-defined areas of interest, or shallow-water areas, in order to avoid them [9]. Third, the optimal route should be efficiently detected without the need for extensive computational resources [9]. Fourth, accurate WR requires temporally fine-grained weather data, fused from multiple sources onto a unified grid [10].

We present the Weather Routing service of VesselFront (VFWR), i.e., a weather routing service addressing all of the aforementioned requirements, and exhibiting the following features:

- We constructed a variable-resolution grid which becomes more dense near coastlines to maximize navigational safety. We make use of the A* algorithm which is able to guarantee the computation of the optimal route with the optimization criterion being sailing time.
- The user may define various constraints, including no-go areas, maximum wave height conditions and northern position during the trip, and cost-effective demands such as minimizing the time spent within an emission control area (ECA).
- We take advantage of a wealth of real historical mobility data, i.e. past vessels voyages, in order to bootstrap the process of weather routing, thus ensuring the computed routes are in line with human expertise.
- The provision of accurate weather data is facilitated by AlongRoute, our weather provider. This information subsequently contributes to the definition of the optimal path.

II. System Description

We designed a dense grid, so as to accurately capture weather variability across spatial transitions during a voyage.

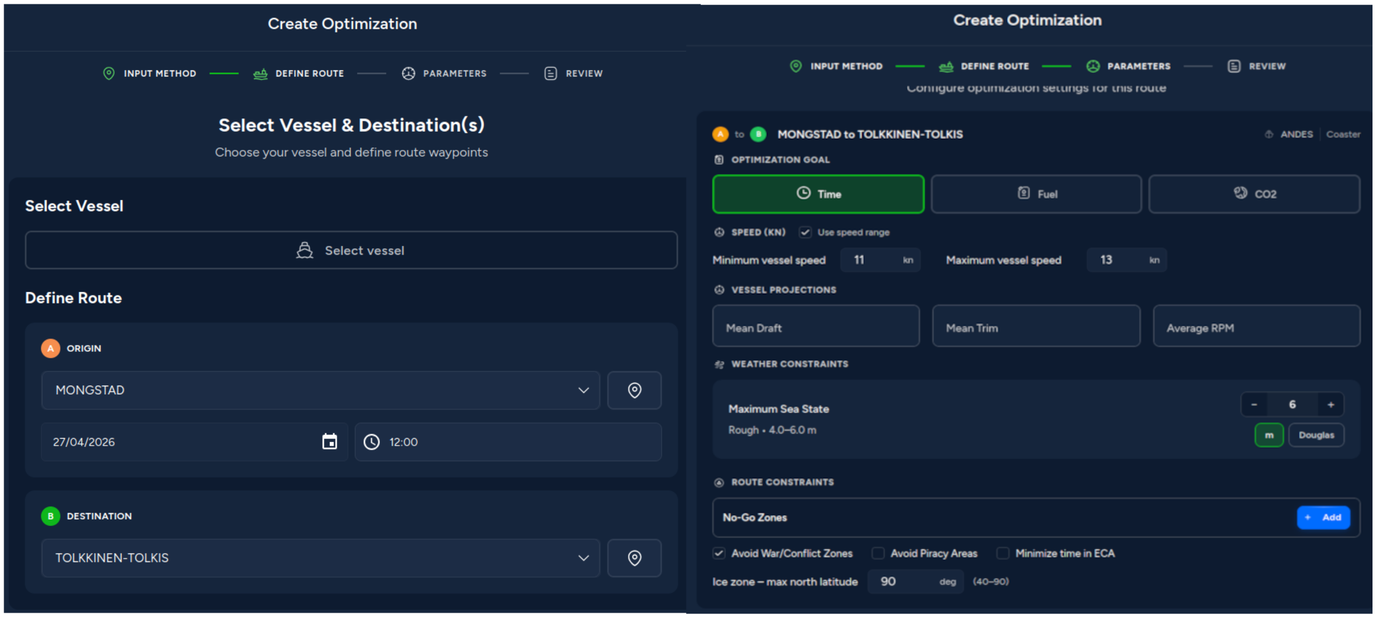

Fig. 1. Input pages of the VFWR platform.

To further account for navigational safety, the grid density is adaptively increased close to the coastal regions and port areas, where maritime traffic intensifies and stricter operational restrictions apply. For the grid representation, we utilized more than 16M nodes. In order to guarantee the computation of the optimal route, we utilize the A* path-finding algorithm. The key property enabling A* to ensure solution optimality lies in its heuristic function, which directs the search toward paths more likely to yield the optimal solution while pruning those that deviate from it. We formulated the heuristic function to incorporate meteorological conditions as a factor in the decision-making process, with the objective of identifying the optimal route based on minimum travel time. Taking all of the above into consideration, the designated heuristic function remains admissible, thus guaranteeing the optimality of the proposed solution.

The user of VFWR has the option to select certain constraints, as seen in Fig. 1. These include spatial constraints, namely no-go areas and the northernmost position that the route may reach during voyage optimization, as well as meteorological constraints, i.e., the optimized route should not traverse points in which the wave height exceeds a predefined maximum value. It is also a common requirement that the route spends the minimum necessary time within ECA zones, which the user may apply or not, leading to a trip-based preference setting.

Since the minimum required water depth varies depending on the vessel's loading condition - whether ballast or laden - VFWR accommodates the vessel's draft as a user-defined input parameter (see Fig. 1). Additionally, the user must specify the start and end points of the trip, the desired departure date and time, and the required speed, i.e. a range or constant value. Furthermore, the vessel of preference must be selected for the designated trip, as the length of the ship is taken into consideration for the calculation of the adjusted velocity that the ship will travel with. This can be done by selecting a vessel previously added by the user's organization.

Given the scale of the grid and the consequent size of the search space, historical mobility data was leveraged to guide and constrain the optimization process. A dataset of 190 historical trips with a median duration of approximately 2 days (maximum duration was approximately 30 days) enabled us to create a data-guided reduced search space, thus ensuring an efficient solution in terms of execution time.

Fig. 2 presents the output of VFWR for a trip from Mongstad to Tolkkinen-Tolkis, illustrating three routes available for immediate comparison: the yellow continuous line illustrates the optimized route based on meteorological data, the blue dashed line indicates the shortest distance path, and the blue continuous line represents the historical route. The optimized route respects two categories of safety constraints. First, it avoids traversing near coastlines and islands, thus maintaining the required safety margins. We hereby note that in narrow passages such as canals and straits, where the ship has no alternative, the route will necessarily appear close to the coastlines. Second, the route avoids shallow waters by accounting for the vessel's draft, as defined in the initial configuration. Beyond safety, VFWR also seeks to avoid adverse meteorological conditions as much as possible, as showcased near Norway and in the Baltic Sea. In this particular instance, the VFWR-optimized route achieves a shorter duration than the historical route. In addition, while the optimized and

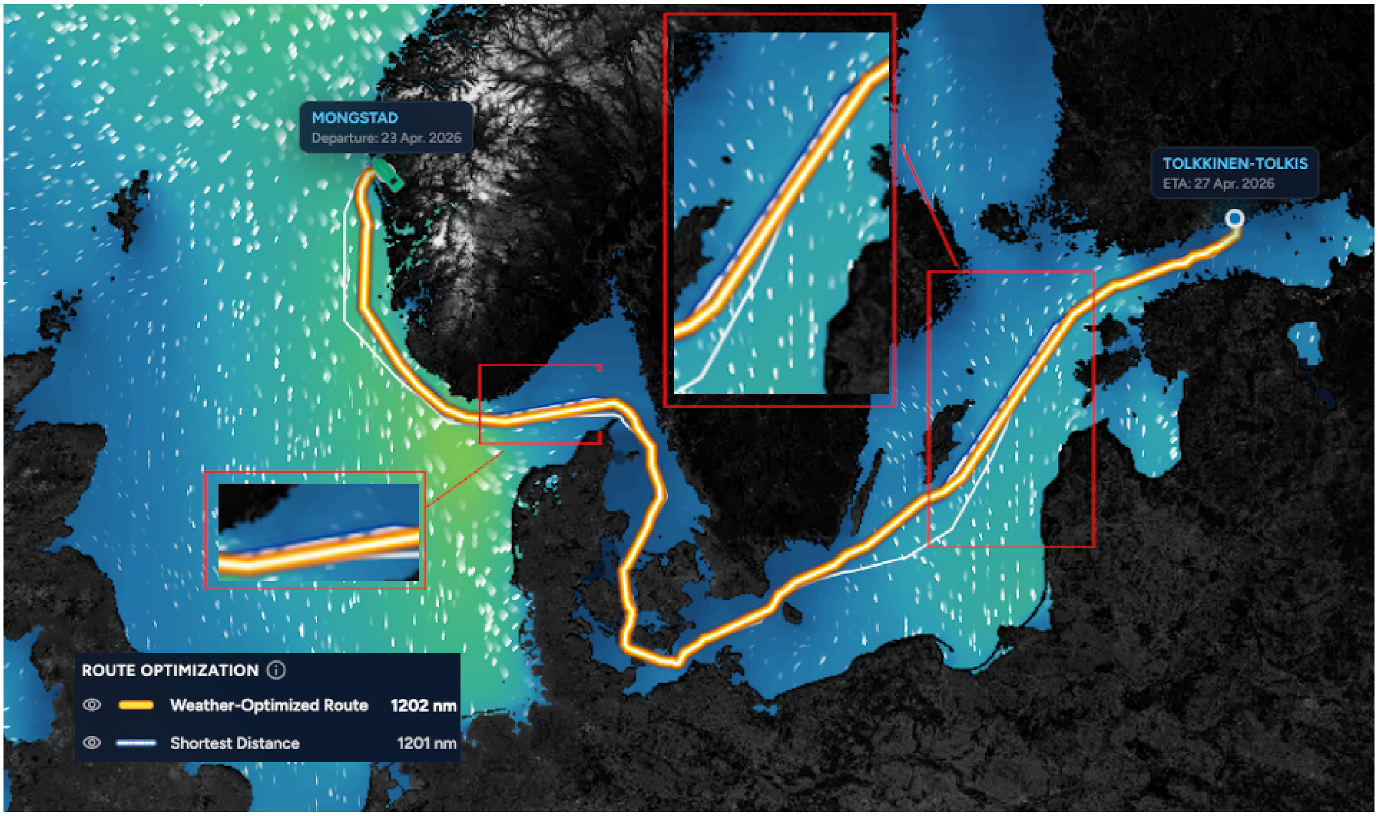

Fig. 2. VFWR in action. The areas in red boxes showcase the difference among the optimized route (orange line) and the shortest distance line (dashed blue line), while the continuous blue line indicates the historical trip.

shortest-distance routes largely coincide in this given example, this is not the case in other instances where VFWR produces routes that are both shorter in duration and safer than the one operationally executed, as will be demonstrated in the following section.

We obtain weather data on the points of our grid from our weather provider AlongRoute who delivers AI-powered marine weather forecasts [11]. While meteorological prediction accuracy is generally reliable up to approximately three days, we perform the optimization over a fifteen-day forecast window. The rationale is that early-stage routing decisions may significantly influence the overall trajectory of the voyage. Hence, incorporating an extended horizon allows VFWR to identify route patterns that would otherwise be overlooked, ensuring that the optimization accounts for the full navigational context of the trip. In long-lasting trips, we perform the re-routing procedure in order to retrieve updated weather data every six hours. This timeframe corresponds to the interval at which the weather provider updates its forecasting data. Subsequent to this, we provide the updated route to the user, incorporating the recently acquired data.

III. Empirical Analysis

We conducted a performance evaluation of VFWR through a comparative analysis against real historical trips. The median execution time required for the calculation of the optimized route was 23 seconds, for routes with a median duration of 46.92h based on the historical data.

Route quality is evaluated separately through duration comparison between VFWR-optimized and historical routes. As shown in Fig. 3, VFWR consistently produces shorter trip durations across all historical duration bins, with improvements ranging from approximately 1 to 6 hours. These results demonstrate that VFWR delivers geographically accurate routes that improve upon real-world navigational decisions in duration, within computation times that are practical for utilization on real-world operations.

IV. Demonstration

Attendees at the conference will have the opportunity to interactively engage with VFWR through a live web interface and set a trip of their preference. A pre-configured baseline scenario - the Mongstad to Tolkkinen-Tolkis voyage presented in Fig. 2 - will be available as a reference point, alongside the option for attendees to define a custom trip. Attendees will be able to specify the departure and arrival ports along with the desired departure date and time, configure constraints including no-go zones which may be selected from pre-defined options or manually drawn at the time of use, and indicate whether the trip should minimize time spent within ECA zones. Additionally, users may specify a maximum wave height threshold for the route and a northern position value,

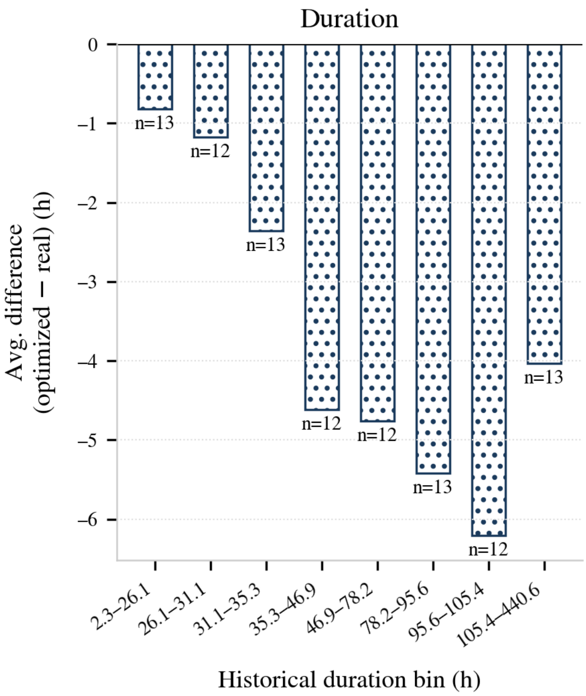

Fig. 3. Reduction in the duration of optimal routes vs real historical data.

while a draft value must be provided to ensure shallow-water avoidance. A desired velocity, either as a range or a constant value, is also required as input. Prior to submission, users will be asked to review all of their previous selections. Upon submission, they will be redirected to the main page where the optimized route will be retrieved and displayed. The demonstration will highlight the real-time responsiveness of the VFWR optimization framework, the effect of individual constraints on the computed route, and the immediate visual comparison between the weather-optimized path and the shortest-distance route. Finally, the users will be able to observe a simulation of the trip alongside the weather conditions present at three-hour intervals along the route.

V. Concluding remarks

We presented VFWR, a WR optimization algorithm based on minimization of travel time. The user is able to provide the necessary input, which is subsequently utilized to calculate the optimal path. Concurrently, re-routing is executed at specified intervals to ensure the maximum accuracy of weather-based optimization. Expert operators on the shipping industry, beyond typical users, are at present able to utilize this tool to immediately attain the resulting trip. Subsequently we performed a validation procedure using real historical data, thus highlighting the effectiveness of the proposed framework.

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