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Original article

Modeling and Optimization Algorithms in Ship Weather Routing*

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Abstract

Efficient and sustainable sea transport is a key aspect to ensure cost competitive ship operation. The constant need to increase economic feasibility, energy efficiency and safety while complying with emission regulations motivates further developments and improvements in voyage optimization and weather routing systems. These systems optimize a voyage based on meteorological and oceanographic information taking into account ship characteristics and routing information. The quality of the provided route not only depends on the quality of this data, but also on the modeling of the optimization problem and the algorithm chosen to solve it. Due to the wide range of mathematical approaches and consequently challenges in decision making, this paper aims to give a comprehensive and comparative overview of the existing state-of-the-art methods by a thorough literature review and elaboration of different modeling approaches, optimization algorithms, and their application in weather routing systems. The research shows that approaches range from modeling the weather routing problem as a constrained graph problem, a constrained nonlinear optimization problem or as combination of both. Based on the formulation of the ship weather routing optimization problem different methods are used to solve it ranging from Dijkstra's algorithm, dynamic programing and optimal control methods to isochrone methods or iterative approaches for solving nonlinear optimization problems. However, it can be concluded that the determination whether an approach is suitable, produces sufficient results and may be recommended, strongly depends on the specific requirements concerning optimization objectives, control variables and constraints as well as the implementation.

Keywords: Weather routing, Mathematical modeling, Optimization problems, Voyage optimization, Algorithms

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I. Introduction and Methodology

Optimizing a ship's voyage is one of the main objectives of a shipping company in order to be cost competitive. It is significantly driven by the need to operate a ship as cost efficient, energy efficient and safe as possible during every voyage in its lifetime. Voyage planning is supported by weather routing systems on a large number of vessels nowadays. Meteorological and oceanographic information as well as ship characteristics and routing information provide the basis to optimize each voyage. Depending on the requirements of the ship's operator and the shipping business, the main objective can be to optimize a ship's voyage concerning energy efficiency, voyage duration, safety or combinations of these aspects. In case of a flexible time of arrival, a minimum time or minimum total cost optimization problem needs to be solved. Often, though, a fixed arrival time is obligatory while the objective is to minimize fuel costs. Besides time constraints, further restrictions include ship characteristics, safety considerations and geographic conditions that are mainly routing restrictions due to land, shallow waters, icebergs, mines or traffic separation schemes. Ship characteristics are mostly considered by a hydrodynamic model reflecting the ship's behavior and responses, its speed profile and fuel consumption when facing wind, waves, current and other environmental conditions.

The ship's speed is influenced by its engine power as well as its calm water and added resistance potentially leading to involuntary speed reductions, while voluntary speed reductions aim to increase safety. Thus, constraints may refer to the maximum available engine power or to speed limitations. Besides the ship itself weather conditions have a great impact. They may be characterized as constant or stochastic. The latter are obtained by considering not only forecasted but also analyzed historical data, hereby accounting for possible forecast errors. Constant weather conditions, in contrast, can refer either to the assumption of neither wind nor ocean current, or to the adoption of the forecasted data as true data for each location at the respective time of passing. In addition, safety requirements such as maximum allowed wave heights or critical encounter periods and angles are crucial to avoid critical occurrences such as slamming or parametric rolling.

Considering these constraints and the objective function, the geographical position and time at each waypoint can be optimized implying the integration of route and speed optimization. However, all derived voyage plans are predictions with a quality not only dependent on the accuracy of the ship's hydrodynamic model and the weather forecasts but also on the choice of mathematical model and algorithm. Weather routing problems can be modeled as nonlinear continuous optimization problems or discrete optimization problems by discretizing space and/or time. A wide range of solving methods varying from methods in optimal control theory, and dynamic programming to Dijkstra's algorithm can be used to find local or global best routes for ships. The proposed methods utilize either single-objective or multi-objective optimization. Furthermore, the methods differ as to the number of control variables. Typically, either the ship's heading or its engine power may be varied in order to optimize an objective function (e.g. travel time or fuel consumption), or only variations of one condition are considered. For example, one may assume constant engine power and optimize travel time by finding the series of ship's headings resulting in the most favorable exploitation of present weather conditions.