



## Ship weather routing: A taxonomy and survey

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# Ship weather routing: a taxonomy and survey

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# Ship weather routing: a taxonomy and survey

## Abstract

Ship weather routing has seen considerably increasing attention in recent years in both academia and industry. Problems in this area consider finding the optimal path and sailing speed for a given voyage considering the environmental conditions of wind and waves. The objectives typically consider minimizing operating costs, fuel consumption, or risk of passage. This paper presents a survey of weather routing and voyage optimization research in maritime transportation, explaining the main methodological approaches, and the key disciplines that are dealing with this problem. The main methodologies used to solve the weather routing problem include the isochrone method, dynamic programming, calculus of variations, the use of pathfinding algorithms and heuristics, while in recent years artificial intelligence and machine learning applications have also risen. Most of these methodologies are well established, and have not changed significantly throughout the years, although applications with a combination of these methods have been used. A taxonomy is subsequently presented based on the discipline, application area, methodological approach, and other important parameters. Considering the steep increase in the number of research papers published in recent years, this paper also seeks to propose future research topics in the field. The paper highlights the need to standardize the reporting of savings through weather routing, to facilitate comparisons between methodologies, which could be achieved through the creation of benchmarking instances.

## 1 Introduction

### 1.1 Background

International shipping moves approximately 80% of global trade by value (UNCTAD, 2019), and remains the most fuel- and cost- efficient mode of transport. At the same time, increasing regulatory pressure to achieve greener maritime transportation, coupled with the volatility of fuel prices, has resulted in a quest to minimize operating costs. Due to economies of scale, even a small percentage reduction in operating costs can lead to savings of millions of dollars in the economy of a ship operator. Once a voyage has been planned from port A to port B, the speed and route that the vessel follows are key determinants of operational efficiency in maritime transportation. For all types of shipping, be it in the tramp or liner market, or whether it is short-sea or deep sea-shipping, there are significant economic drivers to optimize each voyage, considering that for certain shipping sectors

the bunker costs can exceed 50% of a carrier's costs when sailing speeds and fuel prices are high (Alizadeh et al., 2004; Ronen, 2011).

Costs can be reduced in all aspects of maritime transportation, with interesting problems spanning from the selection of the best vessel for the journey, finding the optimal sailing speed in a specific voyage, to complex liner shipping design problems with millions of different possible solutions. There has been a vast number of studies on voyage optimization in all sectors of shipping with various applications and different objectives sought. Some of these problems were first defined decades ago in rather simplified forms, but with the increased computational power available complex instances can now be solved. Given the increased available computational power, the improved quality of weather data and predictions, the increased interest in autonomous vessels, and the drive to reduce emissions from ships, the field of ship weather routing has seen an increased academic and industry interest in recent years, and is expected to receive even more attention in the near future. Ship weather routing is an interdisciplinary problem that has attracted the attention of ocean engineers, computer scientists, data scientists, maritime economists and transportation engineers. The purpose of this paper is to provide a thorough literature review of research in the fields of weather routing within the broader family of voyage optimization problems and identify certain gaps in the literature as well as fertile grounds for new research.

Perhaps one of the most ancient problems in maritime transportation has been the selection of a route from point A to point B, taking into account information on the weather, the sea state, the currents, as well as the depth of the sea at each point. Weather routing has been given several different definitions in the literature depending on what criteria the route planner seeks to satisfy. Simonsen et al. (2015) consider weather routing as finding the optimum route with respect to the expected time of arrival (ETA), passing waypoints, sailing speed, power output, for a certain voyage based on weather forecast data and a given ship's technical characteristics. In the context of our survey, it can be defined as the decision making process with the objective of selecting the optimal route in a given voyage (known origin port and known destination port) taking into account the expected weather and sea conditions. The optimality of the selected route depends on the selected objectives which can range from minimizing costs, travel time, or emissions, to reducing potential delays and lowering risk by avoiding certain areas with adverse weather.

A clarification is in order as regards terminology and specifically what academics and practitioners in maritime transportation may define as "ship routing" and its relationship to weather routing. The "ship routing problem" (or as many times known as the "ship routing and scheduling problem") is a

*distribution problem at the tactical level* in which a ship, or a fleet of ships, have to serve several ports in order to pick up and deliver cargoes, subject to various constraints such as ship capacity, time windows, and others. In that sense it is an extension or variant of the well-known Traveling Salesman Problem or and can be solved by techniques in the Vehicle Routing Problem (VRP) class. The literature in this area is vast, see for instance Christiansen et al. (2013) for a survey. By contrast, the ship weather routing problem is a *path problem for a single ship at the operational level*, in which a ship has to go from a given port A to a given port B, and in which conditions along the path, such as weather, waves, and others are not constant, and the path itself together with the speed profile along the path is optimized according to a specified objective. In that sense, the ship weather routing problem is a very different problem from the ship routing (and scheduling) problem as defined above. Thus, it cannot be considered as an extension of the latter problem, even though one could conceivably consider combined problems, that is, ship routing and scheduling problems in which weather information on each leg of the route is added and the paths between consecutive port calls are optimized at the operational level. More on this class of problems and especially as regards green routing can be found in Section 4.4 of this paper.

In recent years the name of *environmental routing* has been proposed as a more fitting title as it incorporates environmental influences in the search for the shorter or more economical route. For instance, Christiansen et al. (2007) note that the terms *environmental routing* and *weather routing* are frequently used interchangeably, but note that the latter is a subset of the former. Weather (in this case winds, waves, currents) is part of the environment in which ships operate, and it affects the performance of the ship. We should note that the term *environmental routing* in this context refers to the underlying weather conditions and environment (depth of sea, regulated areas requiring different fuel used) in which ships operate at, and should not be confused with the environmental performance of a voyage. Selecting the route that optimizes a voyage in terms of environmental performance (for instance minimization of ship emissions) can be part of the *green ship routing problem* which we shall consider in section 4.5.1 of this paper.

As *minimizing risk* has been mentioned thus far as one of the potential objectives in research on weather routing, perhaps an explanation on what constitutes risk is necessary. Risk in weather routing can be given many definitions depending on what the ship operator would wish to avoid by relying on information on weather. For example, Szłapczynska and Smierzchalski (2009) perceive wind as a primary safety threat in a voyage, and seek to minimize voyage risk, or time spent at areas of high wind. However, as they use multicriteria optimization minimizing risk can increase total sailing time

which can be an alternative objective of ship weather routing. Delitala et al. (2010) consider as a safety risk the likelihood of the ship sailing in areas with waves of a height higher than 4m. Fabbri et al. (2018) consider the navigation risk based on sailing conditions following the IMO guidelines for navigators (IMO, 2007). What weather conditions (wave height and length, wind) would constitute a safety risk depends on the specifics of a voyage (ship type, ship condition, geographical area). Such environmental factors can be incorporated in ship weather routing models by minimizing fuel consumption, considering that it is possible to estimate the fuel consumption within an area of adverse weather effects. Li et al. (2011) provide a thorough overview of risk assessment models in narrow maritime waterways focusing on frequency of accidents and severity thereof, without however examining the impacts of weather. Other definitions of risk could focus on monetary aspects of a voyage, by for example measuring the risk of failing to reach the next port of call within a specified time window which could incur fiscal penalties (Fisher and Rosenwein, 1989) due to contracts with shippers, or simply the increase operating costs due to the increase in fuel consumption if caught in areas of poor weather conditions (Lindstad et al., 2013).

Craft (1998) described how back in 1870 the United States Congress established a national weather organization to issue weather warnings for storms in the Great Lakes as a means to reduce shipping losses. James (1956) was among the first to show that the main reason for loss of speed can be attributed to wave action, and proposed methods for using prognostic wave charts to find minimum time paths. In one of the first academic studies that considered the effects of weather, Hanssen and James (1960) presented the system used by the United States Hydrographic Office to apply predictions of wind, waves, and currents with the objective of providing routes for transoceanic crossings. At the time, the objective was to reduce travel time and the average reduction accounted to 13.2 hours due to a combination of using shorter routes and avoiding delays while the authors suggested that the fuel consumption and time saving benefits could amount to over 2M\$ per year, which at the time was very high. Motte (1972) provided a nice overview of the process of weather routing (notably spelled “routeing”) and emphasizes that a weather forecast of 24 hours was at the time sufficient.

Adverse weather can lead to loss of life in all types of shipping. Roberts et al (2014) conducted a survey on fatalities among seafarers and found that cargo operations taking place in bad weather conditions were a high risk. Poor weather conditions, combined with other factors, have resulted in notable maritime disasters carrying crew and passengers such as the El Faro in 2015 (hurricane), the Costa Concordia in 2012 (weather impacted the salvage operations), the Express Samina in 2000, the

Estonia in 1994 (rough weather), the Derbyshire in 1980 (typhoon) and others. When it comes to shipping in adverse weather areas, weather forecasts in the Arctic can be very important as shown by Ghosh and Rubly (2015) as Arctic shipping routes can significantly reduce fuel consumption compared to other routes, but are very susceptible to weather.

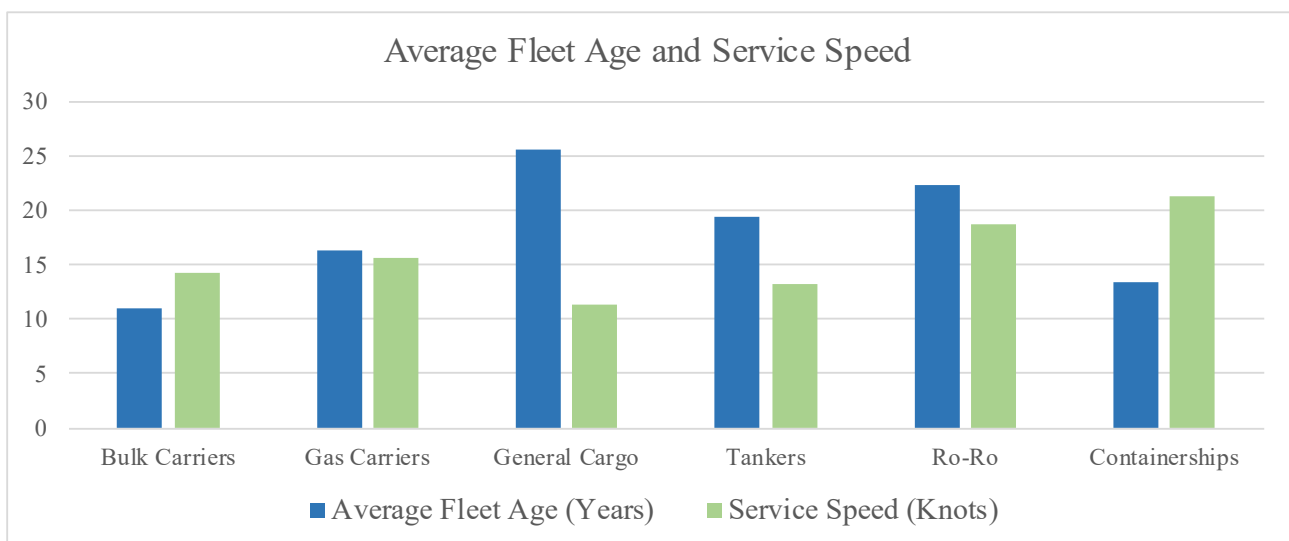
Apart from mitigating the risk of maritime disasters, weather routing can also be of paramount importance to the reliability of a maritime service, and to reduce the operating cost of a voyage. For instance, the World Shipping Council (2018) reports that based on a survey among its members, an estimated 568 containers per year were lost at sea between 2008 and 2016, a number that rises to 1582 containers if catastrophic events such as ship groundings and collisions are included. While weather routing is not the only factor that can conceivably reduce losses of containers at sea, it can certainly play a role. From an economic perspective, sailing in poor weather conditions results in higher fuel consumption while it pertains the risk of a delayed voyage which may in turn have additional demurrage costs (Gershanik, 2014). Finally, from an environmental perspective a reduction in fuel consumption is translated into reduced CO<sub>2</sub> and SO<sub>x</sub> emissions. However, we should note that there may be environmental trade-offs where despite the reduced fuel consumption certain emissions (such as particulate matter) may increase due to the operation of the engine at lower loads (Zis et al., 2014). Armstrong (2013) provided a review of different options to optimize vessel operations with an objective of lowering carbon emissions, and lists weather routing as one of the key operational options.

## 1.2 Sailing speed in a voyage

Before an optimal route considering weather can be designed, it is important to plan the voyage time and obtain the departure time from one port, and the ETA at the next port of call. For all shipping sectors key decisions in the service planning process include the number of ships deployed, the average sailing speed (or voyage duration), and the number of port calls (Agarwal and Ergun, 2008). Each of these decisions depends critically on the shipping sector, the existing market conditions, the availability of ships, the provision at each port to handle a ship, and last but certainly not least, the fuel price. Assuming ideal weather conditions with no wind or waves (calm waters), it would be easy to show that the sailing speed should be constant throughout the duration of the voyage if possible in order to minimize fuel consumption. As with road traffic on a flat road, each acceleration and deceleration would increase the total fuel consumption. A ship operator should therefore in theory opt to maintain a constant speed throughout each cruise leg. In practice this is not happening for various reasons mainly of commercial nature. For example legs carrying predominantly time-

sensitive cargoes might require a higher sailing speed (Zis and Psaraftis, 2017). In bulk shipping the optimal sailing speed is different for laden conditions compared to ballast (Gkonis and Psaraftis, 2012). Other legs might be faster due to currents assisting the vessel, whereas for legs in the opposite direction the current may result in lower sailing speeds. Considering the weather effects the ship operator may have to slow down during worse weather and speed up during calm periods. Many ship operators may choose to speed up during the early stages of a voyage in order to produce a buffer time in anticipation of unexpected bad weather in the later stages of the voyage, or simply to ensure a safe passage by avoiding a storm. The opposite is also feasible if for example the next port of call signals to the ship operator that it will not be ready to receive the vessel, and in order to save fuel suggests a later arrival time, in a concept known as virtual arrival (Jia et al., 2017).

In terms of ranking ships according to their design speed, typically the liner shipping sector has the fastest fleet, with containerships being the fastest and Ro-Ro/Ro-Pax ships being the second fastest, and slower vessels belong to the liquid and dry bulk sectors. General cargo vessels are the oldest and the slowest ones. Figure 1 presents the design speed of the world fleet per category and the average age of each fleet in years.



**Figure 1: Design speed (knots) and ship age as a function of ship age (years) for different types. Data source: Clarkson’s World Fleet Register**

Data from the World Fleet Register suggest that the design speed of newly designed vessels is slightly lower compared to older vessels. This reflects a general trend of going slower for a variety of reasons (depressed market conditions, fleet overcapacity, lower emissions, and others). The impacts of adverse weather on fuel consumption are higher for older less efficient vessels, and the same is true



for faster vessels as the power requirement is increased to maintain speed. As we will present in our taxonomy in section 3, the majority of case studies on weather routing problems is focused on containerships and bulk carriers.

As regards the environmental dimension, Psaraftis and Kontovas (2009) showed that containerships are the highest emissions producers in the world fleet due to their higher sailing speed that requires larger propulsion engines. Notteboom and Vernimmen (2009) analysed the impact of the higher fuel prices observed in the previous decade and how the liner shipping sector adapted to that via slow steaming, increasing the number of deployed vessels, and balancing the number of port calls with the duration of the visit at each port of call.

A clarification is that ships do not trade at predetermined speeds, and the sailing speed of each voyage is not necessarily equal to its design speed; it will depend on a number of factors, as well as who is making the decision. For example, in the spot market the operator may choose the sailing speed as a function of fuel price and the market spot rate. During depressed market conditions and due to the overcapacity of available vessels the sailing speeds tend to go lower. The same can occur when bunker prices are too high, as these were in previous years that led to a significant resurfacing of slow steaming. Research has shown that weather routing can lead to significant fuel consumption savings per voyage that will depend on the sector (faster ships will enjoy higher savings). In the majority of the papers reviewed in this survey, fuel consumption savings are typically reported to reach values between 3 and 5%.

### 1.3 Structure of the rest of this paper

Section 2 presents a bibliometric analysis highlighting the growth of academic research in the area in recent years as well as the increased interest in the industry providing a summary of commercial software available. Section 3 presents the basics of modelling the power requirements of a vessel and subsequently fuel consumption taking into account weather information. We conduct a literature review in Sections 4 and 5 to map and evaluate the body of literature in the field. We present the main methodologies used to plan a route given weather information, and we discuss the necessary data required. We provide a taxonomy of the relevant literature based on the objectives in each of the examined works. In Section 6 the manuscript concludes with a summary of the findings in this paper and with the identification of some research gaps that the academic community could address in future research.

## 2 Research interest growth in ship weather routing

Conducting a literature review has the objective of mapping and evaluating the body of literature in order to propose research questions that can further develop the knowledge base (Tranfield et al., 2003). In most literature reviews the methodology follows an iterative cycle of defining suitable keywords and searching in appropriate databases to analyse the findings. Notable recent examples of systematic literature surveys that have inspired this paper are the works of Fahimnia et al. (2015) using a five step approach for research in supply chain management, and that of Davarzani et al. (2016) where a four step approach is used to analyse green ports and maritime logistics. In this section we provide a breakdown of retrieved papers by main discipline, publication outlet, and subsequently methodologies used.

### 2.1 Deducing the appropriate search terms and initial search

The initial step in this review was to identify keywords for the data collection of published manuscripts in the research area of weather routing and voyage optimization. This process was completed following a number of trial and error attempts where each time the resulting articles and journals were checked to ensure appropriate coverage. For example, if a very generic term such as “Route Optimization” was used, many of the results would include papers in other modes of transportation (there is a vast literature on Vehicle Routing problems, see the comprehensive review of Toth and Vigo, 2002) which are not relevant for our task. At the same time, a search of “maritime routing” would return several papers that focus on network design or inventory routing without taking into consideration weather aspects. As a result it became clear that in order to narrow our search a variety of keywords as well as some combinations thereof had to be used. The keywords we have used include “Weather Routing”, “Ship”, “Maritime“, “Voyage Optimization”, and “Environmental”. We used these key words in the “title, abstract, keywords” search in the Scopus database and stored journal articles in the search. We used Scopus instead of Web of Science as it is more comprehensive than the Web of Science database considering that the latter only includes ISI indexed journals and therefore we would run the risk of missing relevant publications at newer journals. Table 1 provides the breakdown of the search results for the previous combinations as retrieved during January 2020.

**Table 1: The proposed search terms and initial search results**

Search keywords	Number of retrieved papers	Refined papers (only journals)
Ship AND Weather Routing	270	121

Maritime AND Weather Routing	59	27
Ship AND Voyage Optimization	214	122
Environmental AND Weather Routing	152	54
Environmental AND Voyage Optimization	33	16
Total (Voyage Optimization OR ship Weather Routing)	545	280

## 2.2 Publication trends and disciplines

There has been a much higher interest in the field in recent years, with a steep increase of outputs as seen in Figure 2 which excludes papers published in 2020 as the year is not finished.

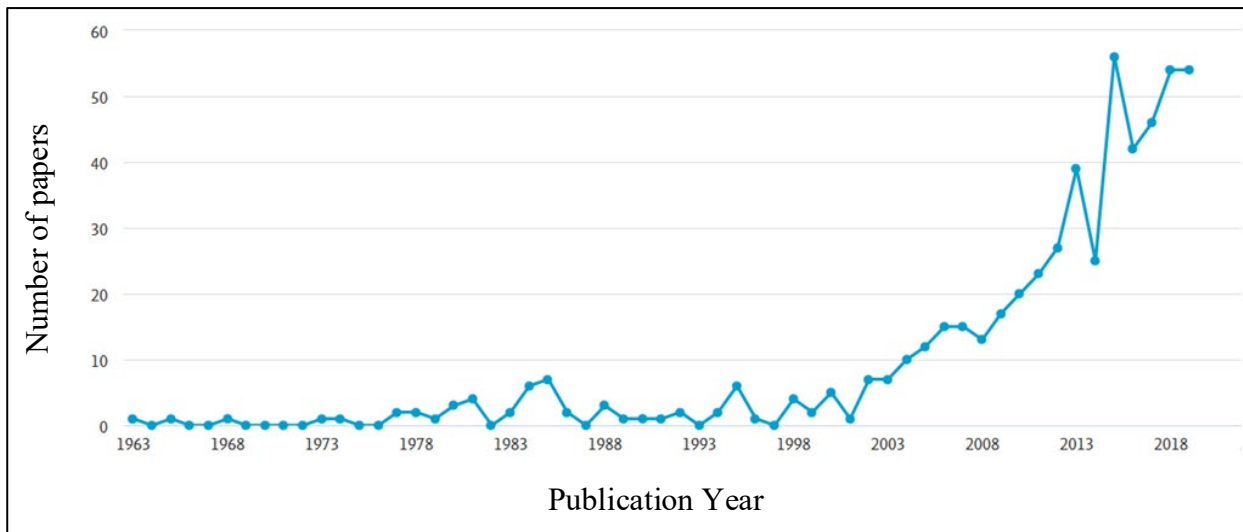
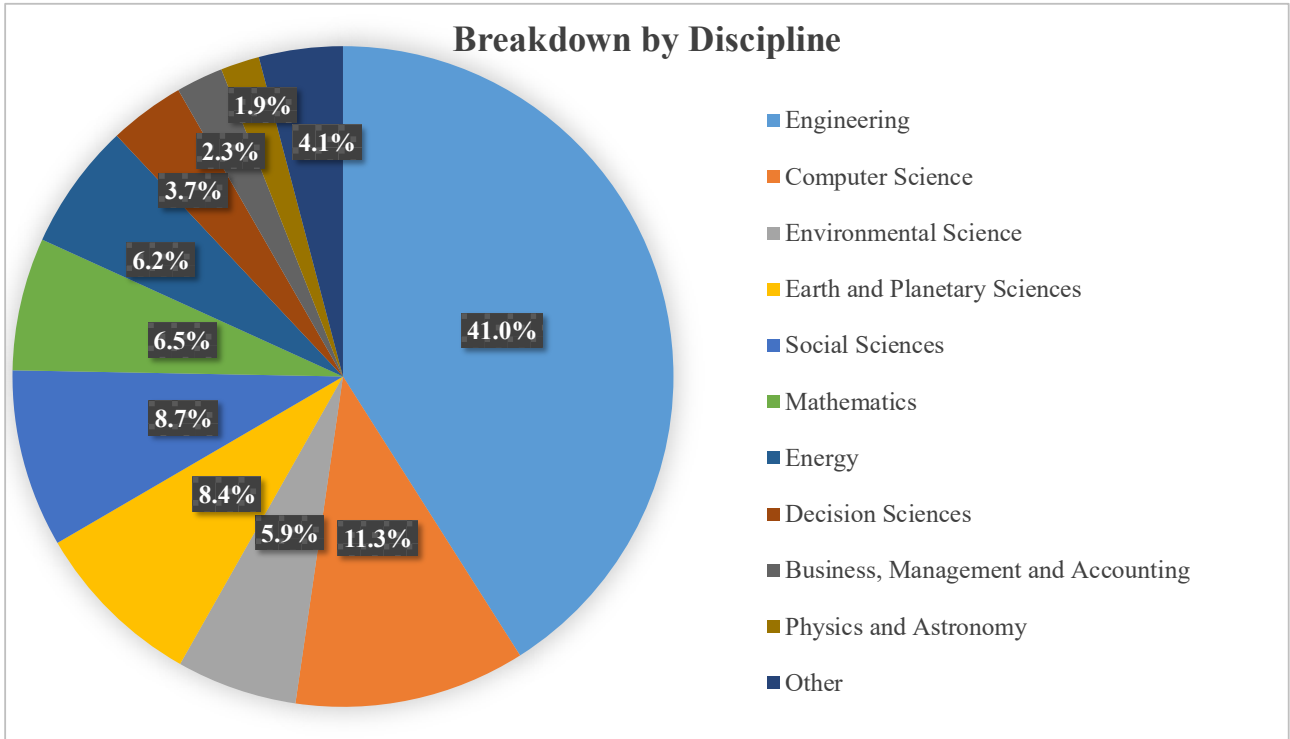


Figure 2: Publishing trend in the area of ship weather routing and voyage optimization. Source: Scopus February 2020

If we consider all results in the two main fields of interest for this paper, then the breakdown of retrieved results in terms of academic discipline can be seen in Figure 3. As expected, it can be observed that the majority of papers fall into the category of engineering (ocean, naval architecture, transportation) and computer science due to the optimization aspects and relevant algorithms deployed.



**Figure 3: Retrieved results breakdown by academic discipline**

The top 10 journals for published papers in the field are presented in Table 2 in decreasing order.

**Table 2: The top 10 publishing journals in the area of ship weather routing and voyage optimization**

Source	1960-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Ocean Engineering	1	2	3	2							3	2	3	5	1
Journal of Navigation											2	1		1	
Applied Ocean Research									1		2	2	1		2
Transportation Research Part C: Emerging Technologies						1	1				2	1		3	1
Computers and Operations Research					2		1				1		1	2	
Journal of Dalian Maritime University						1					1	1		3	
Transportation Research Part B: Methodological					1			1						3	1
Maritime Policy and Management				1	3			1							
Computers and Industrial Engineering									1		1				1
Transportation Research part E: Logistics and Transportation Review					1			1							

### 2.3 Real world interest, market analysis and commercial software

Outside the academic realm, there have been several commercial products developed in the field of maritime routing, particularly in leisure shipping. In fact the IMO has adopted resolution A.528(14) “Recommendation on Weather Routeing” (note the different spelling of the word), which recognizes the importance of weather routing in providing ship operators with optimum routes to avoid bad weather, and improve safety. The IMO recommends to Governments to advise ships under their respective flags to make use of weather routing information, including services by the World Meteorological Organization.

However, few products optimize routes taking into account weather conditions as these require the combined expertise of naval architects, software engineers, meteorologists and oceanographers. In this section for the sole purposes of providing references to readers we summarize different software that are commonly used in the industry that optimize with respect to travel time and fuel consumption, focusing on speed optimization and power utilization. We should note that there is limited information available on the underlying methodologies used in these commercial products. Most of these systems are operating as black boxes with suggestions on the optimal route given the weather information data available through these services. The methodologies used are not as transparent, as one could expect in the case of a commercial application, but information on the resolution of data and length of forecast are typically given. Some of these products are actually extensions of previous academic work that has been commercialized. Academic studies have been focusing on specific routes and ships, given weather data for a specified time period whereas the commercial solutions are designed in a way to provide a route option using real-time information. The latter may not be as refined when taking into consideration the fuel consumption models for a specific ship as in the case of the academic studies. Finally, an important feature is whether a software product is compatible with the Electronic Chart Display Information System (ECDIS).

For the readers’ reference, an indicative cost for a licence of the solution by one of the providers ranges in the area of \$15000 per ship, and subsequently a \$3000 annual subscription fee for technical support. Most of these products are advertising that the expected fuel savings offered to their clients are much higher. Selected software packages and their main characteristics are summarized in Table 3, and the list was compiled based on consultations with stakeholders using these software products, literature of previous work (mainly master’s and PhD theses in the field), and an online search by the authors.

**Table 3: Selected commercial software on ship routing utilizing weather data. Adapted from Psaraftis et al. (2017)**

Software	Bon Voyage System	Seaware Enroute	Sea Planner	SPOS Onboard	Vessel and Voyage Optimization Solution	SMHI (onboard solution)
Objective	Time, Fuel	ETA, Safety, Cost	Time, Fuel	Fuel consumption, ETA	Fuel for ETA	Fuel consumption ETA
Ship Dynamics	Modelling	Specifics Ship Dynamics	Towing Tank Experiments	Specific Ship Characteristics	Ship specific model	Ship and cargo specific
Wind Speed	Yes	Yes	Yes	Yes	Yes	Yes
Tidal Currents	Yes	Yes	Yes	Yes	Yes	Yes
Compatibility with ECDIS	Yes	Yes	Yes	Yes	Yes	Yes
Forecast resolution	2/ 0.125°	Var. / 0.125°	0.1/5°	N/A 4 times/ day	1°	Up to 10 days
Forecast source	Stormgeo	Stormgeo	Danish Meteorological institute (DMI)	DTN (formerly known as Data Transmission Network)	Oceanweather	SMHI (Swedish Meteorological and Hydrological Institute)

In the majority of the reviewed articles in this paper the optimal routes considering weather information have as objective to either minimize travel time, or fuel costs. In order to minimize fuel consumption, the first step is to be able to predict the actual propulsion power requirements and how these change in the presence of environmental factors affecting the trip. The next section provides a brief summary of power prediction in maritime transport, and we provide references of important contributions that contain more detailed information.

## 2.4 Weather forecast data

Weather routing methods can be applied and the extent of possible savings (time or cost) will depend on the quality of weather data. Accurate weather forecast can significantly reduce the risk of sailing and lead to time and cost savings. Chu et al. (2015) show that meteorology and oceanography (METOC) systems can save up to 20% in fuel. Weather forecast contains information regarding waves, currents, wind, and temperature. Short-term weather forecast provides predictions for periods up to one or two weeks, with the accuracy falling as time goes by. Long-term prediction may consider periods of years. The impact of ocean currents fall under the category of long-term data, and significant savings are observed. Lo et al. (1991) reported savings up to \$70 million in annual fuel costs at the time for the world commercial fleet by exploiting currents in routing, largely due to the difference in sailing speeds in different seas due to the currents. Lo and McCord (1995) incorporated ocean currents in their formulation in the Gulf Stream Region and reached savings of 7.4% and 4.5% for the eastbound and westbound directions respectively.

Forecast is produced based on data gathered from satellites, buoys, and local climatological measurement stations. These data are provided by meteorological institutes or commercial companies. Examples include the Navy Operational Global Atmospheric Prediction System (NOGAPS) developed by the Naval Research Laboratory (NRL) and the Navy's Fleet Numerical Meteorology and Oceanography Center (GNMOC). In Europe the Integrate Forecast System (IFS) is developed by the European Centre for Medium-Range Weather Forecasts. The EU has also developed the Copernicus Marine Environment Monitoring Service (CMEMS) that provides wave forecasts using satellite altimetry data, numerical models, and in situ data. CMEMS additionally offers products and services for maritime safety, coastal and marine environment, and climate related issues. We have to note here that when it comes to weather forecast data there are significant uncertainties in place. As Hinnenthal and Clauss (2010) note, deterministic forecasts do not provide information on the reliability of the prediction. To enhance the robustness of the selected routes they suggest ensemble forecasts to capture variability in the weather development. Wang and Meng (2012b) consider the



uncertainties in weather as well as port time at berth by adjusting the sailing speed of ships in their network design and the maximum allowable transit times between port calls. Du et al. (2015) use robust optimization to minimize the total fuel consumption of a ship over a round-trip voyage taking into account the uncertainty in fuel consumption rates caused by weather conditions. Skoglund et al. (2015) compare deterministic and ensemble forecasts in weather routing and show that the latter can reduce the risk of late arrivals. The authors however stress that the use of ensemble forecasts requires significant computational power and propose multi-stage optimization based on these forecasts.

Over the years with increased computational power more accurate data can be processed and high quality wind information can lead to the design of improved weather analysis tools (Perera and Guedes Soares, 2017) and improved savings. Papadimitriou et al. (2019) discuss the potential of space tools, applications, and some initiatives by the European Space Agency (ESA) in order to contribute in reaching the objectives set out in the European maritime related policy areas. Technological advances in satellite altimetry offer the potential for providing timely ocean current information which could be used when optimising strategic ship routes. These methods offer the advantage of more accurately estimating dynamic current velocities and thus facilitate the planning of a better route. In one of the first studies to use satellite altimetry data, McCord et al. (1999) report average fuel savings of 2.5% over 486 simulated voyages through dynamic programming. The authors note that using error-free nowcasts the fuel savings could reach on average 11.1%, thereby stressing the impact of accurate forecasts. However, satellite altimetry data require significant time for collection and processing before delivering the information (optimal path) to the end user, and therefore the information could be an inaccurate description of the actual current patterns in areas of substantial dynamic current activity. Lo and McCord (1998) extended their work to propose formulations that include stochastic ocean currents. Their paper develops an optimisation approach that explicitly addresses the uncertainty resulting from time-lags in the use of satellite altimetry data and processing. They formulate the weather routing problem as an adaptive, probabilistic dynamic program that can outperform deterministic approaches when live satellite altimetry data are not available. The impact of improved forecasts for currents can be significant and result in further reductions in the fuel consumption of a particular voyage compared to weather routing where only wind and wave data are considered. The grid resolution as well as the temporal frequency of updating the data can play a significant role in improving the optimality of a particular route. Depending also on the type of route (for example transoceanic versus short sea shipping) the importance of resolution near straits and coastal areas will also change.

### 3 Power requirement for propulsion

For all shipping activities, the performance of a ship is influenced by the surrounding environmental conditions. In this context the existing winds, the waves, and the currents and tides can be defined as the environmental factors in any voyage. These factors will affect the fuel consumption by changing the power requirements for the propulsion of the vessel. Even though it is outside the scope of this survey to provide a detailed analysis of these mechanisms, this section attempts to presents a summary of the basic concepts.

#### 3.1 Environmental factors

Each of the aforementioned environmental factors affect the performance of the ship in a different manner. Waves and winds are interrelated and these have a higher impact in the routing planning due to their evolving nature. Currents on the other hand should not be underestimated and information on these has always been used to generate routes. A ship's resistance is particularly influenced by its speed, displacement and hull form. Once ship resistance has been modelled for all of the environmental factors for a specific ship, then weather routing software can provide more reliable and better routes. The total resistance  $R$  consists of several resistance forces acting on the ship, which we will briefly describe in this section, while also referring to some relevant papers that provide a more thorough and analytical presentation of such methodologies.

This provides a basis to calculate the source resistances acting on the ship by means of dimensionless resistance coefficients. The necessary resistance coefficients can be found through hydrodynamic analysis for specific ships using ship resistance modelling. This consists of using towing tank tests with scale models, developing Computational Fluid Dynamics (CFD) models to simulate the flow around the ship, quasi-experimental methods using results of experiments and calculations, and seakeeping models to estimate ship motions in irregular waves. In terms of CFD applications there are also commercial software that can be used in modelling ship resistance (for example NavCad, STAR-CCM+, Nextflow). There have also been several application papers in the literature using CFD software considering among others the effects of biofouling in ship resistance (Kohr and Xiao ,2011; Demirel et al., 2017).

### 3.1.1 Calm Water Resistance

Water resistance consists of calm water resistance and added resistance caused by waves. Calm water resistance can be calculated through a variety of methods, including theoretical methods and model testing. In general there is no closed form function that can be used to estimate the resistance of a ship as a function of the parameters that affect it, even though there can be some approximations. Calm water resistance is what a vessel would face in the event of total calm weather conditions, with an absolute lack of waves excluding the waves created by the ship. Calm water is very rarely encountered when sailing, particularly in ocean going voyages. Lee et al. (1985) estimate that in the North Atlantic and in the North Pacific the probability of encountering calm water is respectively 0.7% and 1.3%. Calm water resistance typically consists of frictional resistance plus resistance due to waves generated by the ship. Frictional resistance is due to the viscosity of the water which creates friction with the hull of the ship and depends, among other things, on the cleanness of the hull. Cleaning the hull at frequent intervals ensures that frictional resistance is kept at a minimum level, otherwise it will increase due to algae and other material that sticks to the hull. Ship owners usually invest in anti-fouling hull paints to prevent unwanted increase in frictional resistance and thus lead to reduced costs. Mechanisms such as air bubbles generated at the keel of the ship have also been proposed to reduce frictional resistance. Another factor that tends to influence water resistance is the depth of the water, as in shallow waters the ship has a greater difficulty in moving aftwards.

Let  $R_T$  be calm water resistance, it can be calculated as a function of the total drag coefficient  $C_T$ , the  $\rho_{sw}$  density of water, the speed over water  $V_s$ , and the total wetted area  $S$  of the hull.

$$R_T = \frac{C_T \cdot \rho_{sw} \cdot V_s^2 \cdot S}{2} \quad (1)$$

The total drag coefficient is composed by the sum of the friction coefficient  $C_F$  and the residual drag coefficient  $C_R$ . The former is calculated as a function of the Reynolds number (ratio of speed  $V_s$  and length of the ship  $L$  sailing in water of viscosity  $\nu$ ) as in equation 2.

$$C_F = \frac{0.075}{(\log(Re) - 2)^2} \text{ where } Re = \frac{V_s \cdot L}{\nu} \quad (2)$$

In general both components of the calm water resistance of a specific ship are quadratic functions of the ship's speed over water  $V_s$ , and are proportional to the ship's wetted surface  $S$  and to the density of water. However, the coefficients of proportionality are not constant. The frictional resistance is quadratic with speed, since  $C_F$  is essentially constant with Froude number for a given ship size. The residual resistance is mainly due to wave making and is strongly dependent on the Froude number. Residual resistance is thus generally roughly proportional to  $V_s^4$ .

See Schneekluth and Bertram (1998) and Newman (2018) for more information. Calculating these coefficients can be done either by towing tank tests, semi-empirical formulae or CFD calculations. Bulbous bows and slender hulls generally achieve lower wave resistance than fuller hull shapes.

### 3.1.2 Added Resistance

As it is unlikely that the ship will encounter calm weather, extra resistance will be generated by sea waves along the ship's route. This extra resistance is called added resistance and it is heavily non-linear. Estimating added resistance is a complex process, as this generally depends on hull shape, seakeeping characteristics of the ship, the sea spectrum and other parameters, whose analysis is beyond the scope of this paper.

For the calculation of the added resistance we refer to Salvesen (1978) using strip theory approximation. Other important papers on added resistance include Kwon (2008), Bhattacharya (1978), Panigrahi et al. (2012), Joncquez et al. (2008) and Cai et al. (2014).

A simpler method is to estimate speed loss due to waves as suggested by Bowditch (2002), where the final speed is given by

$$v = v_0 - f(\beta) \cdot H_s^2 \quad (3)$$

with  $H_s$  representing the significant wave height, and  $f(\beta)$  is a parametric function on the relative wave direction hitting the ship at angle  $\beta$ . This function will vary with the relative angle, the wave direction and the specific ship. Grifoll et al. (2018b) provide a thorough application of this method to estimate resistance, and subsequently use the A\* algorithm to minimize travel time on a ferry service in the Mediterranean.

### 3.1.3 Impact of water currents

A current can either increase or decrease the speed of the ship depending on its course. Currents can therefore significantly affect the total fuel consumption of a voyage when selecting the route. These can be categorized into global and tidal currents. Global ones, such as the major ocean currents are found permanently in the seas and their position is well known. Ocean currents are not a major issue in the routing problem as these are more predictable than wind and waves (Bowditch, 2002). Tidal currents are occurring due to the gravitational effect of the moon (and to a lesser extent of the sun) on the earth surface. These forces raise the oceans outwards on the opposite sides of the globe, which is translated into a rise in the sea level in these areas and a decrease in the midway. As a result tidal currents are formed that can affect the course of a vessel. Larsson and Simonsen (2014) note that in certain places tidal currents can exceed 10 knots. Bowditch (2002) provides the Golden Gate at San

Francisco as an example of currents of more than 5 knots, and stronger currents of more than 13 knots occurring at Seymour Narrows in British Columbia. Typically information on tidal waves is obtained through tables (for example from the National Ocean Service), or through computer software.

The effect of the current speed to the vessel can also be calculated using analytical geometry, as follows (Windeck, 2013) to estimate the resulting speed  $V_C$ :

$$V_C = \sqrt{V_{CU}^2 + V_{CO}^2 - 2 \cdot V_{CU} \cdot V_{CO} \cdot \cos(\beta_{CU})} \quad (4)$$

Where  $V_{CU}$  represents the current velocity,  $V_{CO}$  the desired sailing speed over ground, and angle  $\beta_{CU}$  the angle between the direction of the current and the ship's heading. This resulting speed  $V_C$  is then plugged in equation 1 to estimate the total resistance.

Cai et al. (2014) provide a more thorough breakdown of the ship resistance calculations for all environmental factors, including currents. For currents they use a ship body-fixed coordinate system and estimate the forces enacting on the ship using empirical drag coefficients of ocean currents.

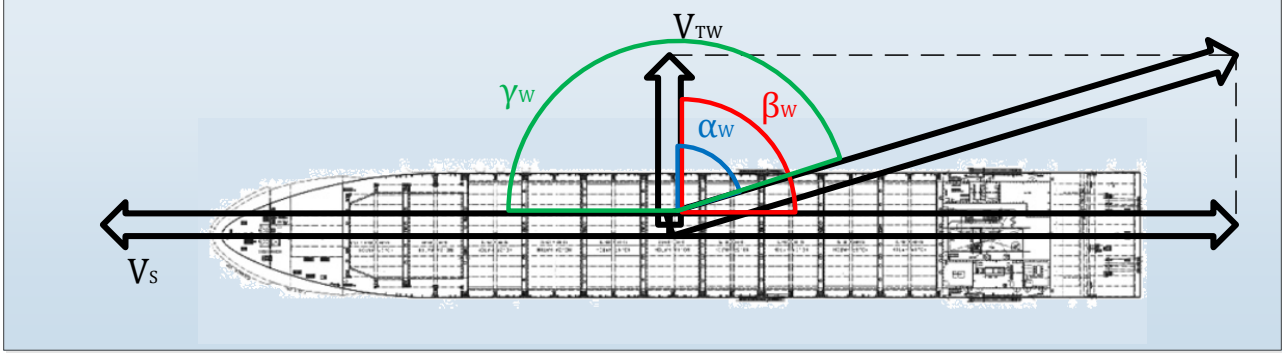
#### 3.1.4 Wind resistance

Winds are contributing to the creation of waves, and at the same time act as a force on the vessel as wind resistance. Wind resistance will affect all surfaces of the ship above sea level as well as cargo when the latter is above the hull. Wind resistance is in principle proportional to the cross-sectional area of the ship above the waterline and the square of the ship's speed when sailing in calm weather. This area is defined by the above-water part of the main hull and any superstructures (e.g. cargo, bridge, equipment). Normally wind represents around 2% of the total resistance, with the notable exception of containerships where due to the large cross-sectional area of the ship (due to containers on-board) the contribution can reach up to 10%.

The wind force is typically divided into two components; the Fair Wind (FW) which is what the ship is facing during sailing (same speed but opposite direction of the vessel), and the True Wind (TW) which is the actual wind speed and direction at the current position at sea. The former is essentially the wind that the vessel would face due to the fact it is sailing, while the latter would be the wind the vessel would face at the same location if it was anchored. Combining these two results in the Apparent Wind (AW) which can then be used to calculate the total wind resistance. This can be simply calculated using analytical geometry as shown also by Windeck (2013). Let  $V_{AW}$  be the vector describing AW,  $V_{TW}$  be the vector describing TW,  $V_{FW}$  be the vector describing FW, and  $\beta_w$  the angle between TW and AW. The scalar of  $V_{AW}$  can be calculated from equation 5.

$$V_{AW} = \sqrt{V_{TW}^2 + V_{FW}^2 - 2 \cdot V_{TW} \cdot V_{FW} \cdot \cos(\beta_w)} \quad (5)$$

What equation 1 describes is depicted visually in Figure 4 for a vessel sailing at speed  $V_s$ , facing a TW from the south.



**Figure 4: Wind direction and calculation of apparent wind**

Having calculated the scalar of AW, the next step is to determine angles that will help the calculation of the wind resistance. Let  $\alpha_w$  be the angle between the AW and the TW. This can be calculated by equation 6.

$$\alpha_w = 2 \cdot \arcsin \left( \sqrt{\frac{(s - V_{AW}) - (s - V_{FW})}{V_{AW} \cdot V_{FW}}} \right), \text{ with } s = \frac{V_{AW} + V_{FW} + V_{TW}}{2} \quad (6)$$

It is then possible to calculate the incident angle  $\gamma_w$  between the direction of motion and the wind and that can be used to calculate the wind resistance  $R_{wind}$  that affects the ship directly based on its trajectory. This wind resistance is calculated by equation 7.

$$R_{wind} = \cos(\gamma_w) \cdot c_A \cdot \frac{\rho_A \cdot V_{AW}^2}{2} \cdot A_{AWS} \quad (7)$$

Where  $\rho_A$  is the density of the air and  $A_{AWS}$  the resulting surface opposing wind direction.  $c_A$  is the air resistance coefficient which varies for different ship types. It takes its larger values for containerships and the exact value depends on the TEU capacity of the vessel, ranging from a lowest value of 0.09 up to 0.18 (Kristensen and Lützen, 2012).

### 3.2 Power prediction, fuel consumption, and associated emissions

#### 3.2.1 Determining installed engine power

Once the main resistances have been estimated, it is possible to calculate the necessary towing power  $P_E$  to move the ship through the water at the required sailing speed. The towing power is the product of the total resistance times the speed over water. Based on that, the required nominal power of the

propulsion engines ( $EP_{main}$ ) can be selected. This will depend on the size of the ship, the mass it will be transporting, and the typical sailing speed during voyage. The engine should cover the propulsion demands considering cost elements (acquiring, operating and maintenance), reliability and adaptability to different operating patterns. The next step is to select the engine that satisfies the propeller's demands and allows the ship to sail at its nominal speed.

The maximum continuous rating (MCR) is the maximum output that the engine is capable of producing for continuous operation. Ships normally operate at the nominal continuous rating (NCR) which is around 85% of MCR when sailing at design speed (Cariou, 2011). The nominal installed power  $EP_{main}$  is essentially the power output at 100% MCR. The engine power produced is limited by application guidelines leaving a power reserve for unusual operating conditions (for example extreme weather, or other emergency). This means that sometimes the engine may operate at higher than 100% MCR, on what is known as overload running. According to Caterpillar Marine, operating time at loads above these levels is limited to 8.3% of total operating hours (one hour in 12) in order to reduce the risk of damaging the engine (Caterpillar, 2010). The same limit (one hour in 12) is also suggested by MAN Diesel (2006).

### 3.2.2 Fuel consumption and basic emissions modelling

After determining the nominal engine power, the fuel consumption of the vessel can be estimated based on the power requirements at each activity phase. Zis et al. (2014) break down the fuel consumption of any voyage into four distinct activity phases; sailing ( $S$ ), anchorage ( $N$ ), manoeuvring ( $M$ ), and at-berth ( $B$ ) fuel consumption. The fuel consumption at each stage is the summation of all currently active machinery on-board. Typically these are the main (or propulsion) engines ( $m$ ) that work during cruise, the auxiliary engines ( $a$ ) that are working at all activity phases (albeit with different power demands) and are covering electricity, ventilation, and hoteling activities of the vessel, and lastly the boilers ( $b$ ) that are used to maintain fuel and marine engine cylinder temperatures. The boilers are working whenever the main engines are not. The fuel consumption  $FC_{e,A}$  (kg of fuel) of any marine engine

$e \in \{m, a, b\}$  during activity phase  $A \in S, N, M, B$

can therefore be calculated by the following general formula:

$$FC_{e,A} = 10^{-3} \cdot SFOC_{e,A} \cdot EL_{e,A} \cdot EP_e \cdot t_A \quad (8)$$

Where  $SFOC$  is the Specific Fuel Oil Consumption (g/kWh) of the engine,  $EL$  dimensionless measure (usually expressed in % terms) which indicates the continuous rating output of the engine in relation to the MCR,  $EP$  is the nominal installed power of the engine, and  $t_A$  (hours) is the duration of activity

$A$  in hours. The  $SFOC$  is a measure of the fuel efficiency of an engine with respect to power output, and it varies significantly at different loads of operation, and for different engine types. The  $SFOC$  is typically optimized to have its lowest value at the engine loads where the engine is expected to run at most times. Sailing is by far the most fuel consuming activity, and it is critically dependent on the sailing speed. During sailing the auxiliary engines are still running at relatively low loads, which are not affected by the sailing speed. However, the fuel consumption of the main engines that are used to propel the vessel is governed by the sailing speed. As shown earlier in section 2, the resistance of a ship is roughly proportional to the square of the ship's speed (see Bernoulli's law), and as a result the power (speed times resistance) requirement can be assumed to be proportional to the cube of speed. This is the origin of the so called "propeller law" that has been used widely in research to model the effects of slow steaming on carbon emissions or fuel costs (see Psaraftis and Kontovas, 2013; Cariou, 2011; Corbett et al., 2009). This law is shown in equation 9 for two different sailing speeds  $V_{S1}$  and  $V_{S2}$ , and their respective engine loads.

$$\frac{EL_{m1}}{EL_{m2}} = \left(\frac{V_{S1}}{V_{S2}}\right)^n \quad (9)$$

In calm water (for example during sea trials) and for low sailing speeds the value of the exponent  $n$  can be safely assumed to be 3, even though this is an approximation. However, often a higher value for  $n$  is used to describe more accurately the relationship between required power and sailing speed. Table 4 provides a summary of frequently used exponents used in the literature:

**Table 4: Variations of the exponent value used in the propeller law**

Vessel type	Exponent	Source
General (valid at low speeds)	3	MAN Diesel & Turbo (2011)
Low speed ships (tankers, bulk carriers)	3.2	
Containerships (based on sample of 2259 ships)	3.3	Notteboom and Cariou (2009)
Medium-sized, medium-speed (feeder container ships, reefers)	3.5	MAN Diesel & Turbo (2011)
Large high-speed ships (containerships)	4	MAN Diesel & Turbo (2011)



Large Containerships (extreme weather)	4.5	Kyrtatos (2011)
Based on a linear regression model on historical data	$2.7 < n < 3.3$	Wang and Meng (2012a)
Ships sailing at higher than 20 knots	$>4$	Psaraftis and Kontovas (2013)

It is noteworthy that using regression techniques (as in the paper of Wang and Meng) there would be instances where the exponent is lower than 3, which contradicts basic hydrodynamic theory. This may be attributed to very low sailing speeds, to the impact of the fuel consumption of the auxiliary engine if the authors took that into consideration, or perhaps using fuel consumption data from voyages where currents reduced the power requirement of the vessel. Alternatively, to estimate fuel consumption at off-design conditions such as rough weather, a sea margin of typically 15 to 25% of the power required in calm water conditions is added (Taskar et al., 2016). In the majority of the literature on transportation research, the fuel consumption takes into consideration only the sailing speed. But the weight of the ship (and thus the weight of the cargo on-board) can also affect the total fuel consumption as shown earlier. There are several empirical approximation models, where for a given speed, the fuel consumption is proportional to the total weight raised to the power of  $\frac{2}{3}$  as in equation 10.

$$FC_{m,s} \propto (cw + ew)^{\frac{2}{3}} \quad (10)$$

Where  $cw$  is the cargo weight (including fuel on-board and consumables) and  $ew$  is the weight of the ship if empty. The book of Barrass (2005) provides more information on the impact of weight on the fuel consumption during sailing.

When it comes to emissions modelling, this has been a recurrent subject in literature particularly after the IMO started commissioning its series of greenhouse gas studies that also provide emission factors (IMO, 2009, IMO, 2013). For most pollutants the emissions generation attributed to marine engines can be found by multiplying the fuel consumption of each machinery with an appropriate emission factor. The emission factors will depend on the engine type, the engine speed (rotation), the fuel used (particularly when it comes to CO<sub>2</sub> and SO<sub>x</sub> emissions), and the engine load as for very low load operations some pollutant types (such as Particulate matter and black Carbon) may increase (EPA, 2002; Zis et al., 2014).

For the readers' convenience we provide a summary of the most commonly used emission factors in recent literature noting that these are only considering fuel burned, and do not account for life-cycle emissions (for example for transportation of fuel from refineries to bunkering ports, or for refinement purposes). For CO<sub>2</sub> traditionally a value of 3.17 has been used which is retrieved by multiplying the carbon fraction of the fuel (typically 86.4%) with  $\frac{44}{12}$  the relative molecular masses of C and CO<sub>2</sub> (12 and 44 respectively). However, the second IMO GHG study (IMO, 2009) suggested using different values depending on fuel consumed, with 3.021 for Heavy Fuel Oil (HFO), 3.082 for Marine Diesel Oil (MDO), and 2.6-2.8 for Liquefied Natural Gas (LNG). Sulphur emissions depend on the sulphur content of the fuel used, and these are again connected by a linear relationship where the SO<sub>x</sub> emissions are found by multiplying the fuel consumed by the percentage of the sulphur content, and subsequently by a factor of 0.02 (Zis et al., 2014). For NO<sub>x</sub> emissions, these depend on the engine speed and values of 0.087 and 0.057 for slow and medium speed engines respectively are typically used (Dolphin and Melcer, 2008).

### 3.2.3 Using underpowered ships in rough weather

The previous section provided a summary of determining the necessary propulsion power for a vessel, given its size, type, and intended use. The effect of weather in increasing the total resistance acting on a vessel was shown, and it can be deduced that avoiding areas with strong weather phenomena can lead to reduced fuel consumption per voyage. Therefore, accurate and timely weather information can be imperative in the fuel economy of the ship operator, as well as for minimizing the potential risks of sailing in bad weather. In recent years the practice of slow steaming has resurfaced as a means to reduce operating costs at times of high fuel prices, as well as to cut down on carbon emissions from international shipping. The latter has been used by the leading shipping companies as a competitive advantage with the design of more fuel-efficient engines and vessels, designed to sail at lower sailing speeds. The lower sailing speeds assisted in the reduction of the contribution of maritime shipping in global CO<sub>2</sub> emissions. The third IMO GHG study (IMO, 2014) estimated international shipping emissions at 796 million tonnes in 2012 compared to 885 million tonnes in the second IMO study in year 2008 (IMO, 2009). To further capitalize on the trend to reduce sailing speeds, newbuilds are now designed to operate at lower sailing speeds, and engine manufacturers have started producing "de-rating" kits that ensure that the SFOC has its lowest values at lower engine loads. Psaraftis and Kontovas (2013) note that this can also be achieved by dropping a cylinder from the main engine. However, this trend could lead into underpowered ships that when attempting to maintain speed at bad weather will end up emitting more than a ship with a larger engine as Psaraftis (2012) notes. With

the previous basics in power prediction and deciding the optimal sailing speed, the next section attempts to highlight how weather information can be used to improve routing.

## 4 Literature Review and main methods used

The main methods used in order to optimize weather routing are the Modified Isochrone method, dynamic programming, calculus of variations, and the application of heuristics (including genetic algorithms) and pathfinding algorithms such as Dijkstra's algorithm (Dijkstra, 1959) and A\* (Dechter and Pearl, 1985), while also applications of machine learning and artificial intelligence are also rising.

### 4.1 Modified Isochrone method

The isochrones method was originally proposed by James (1957), extended by Hanssen and James (1960) to optimize routing in stationary weather conditions. An isochrone is a line represented in a grid, and each isochrone concerns a different possible trajectory of a ship that has the same travel time. At the end of each isochrones a new one is constructed until the final destination point has been reached. This method was adapted and extended by Hagiwara (1989) in what is now known as the modified isochrones method. Hagiwara showed that when environmental factors are taken into consideration the length of these lines will change, and as such the different lengths can be traversed within the same time interval. Hagiwara presented the method to minimise either time, fuel or cost, where the objective function is essentially the definite integral of the cost (that includes a penalty if the vessel arrives late) over the time interval (departure time to desired arrival time). The decision variable is the position of the vessel and a control vector of the vessel's heading and power is used. One disadvantage of the isochrones method is the so called "isochrones loop" that is an irregularity caused by the non-convex power requirement of the vessel for a given sea state. The loop can propagate as the number of isochrones increase, and to address this issue Roh (2013) proposed an improved isochrone algorithm. Lin et al. (2013) proposed the three dimensional isochrones method (3DMI) that allows the ship speed and wave angle to vary at different geographic locations taking into account the variations not only in the weather but also in the water depth. The authors use a floating grid system and a recursive forward algorithm in search for an optimal route in terms of expected time of arrival and fuel consumption.

## 4.2 Dynamic programming

An important number of papers has used dynamic programming in order to optimize weather routing. Dynamic programming is based on Bellman's principle of optimality where a problem is broken down into several stages, and after the first decision all the remaining decisions must be optimal (Bellman, 1952). The decisions at each stage can be found by either working either forward or backward at each stage. In the context of weather routing, Zoppoli (1972) used a discretization of the feasible geographical space to derive closed-loop solutions through the use of dynamic programming. Chen (1978) used dynamic programming by formulating a multi-stage stochastic dynamic control process to minimize the expected voyage cost. Dynamic programming has also been used by Wang (1993) to design routes with the objective of reducing fuel consumption. Shao et al. (2011) proposed a new forward three-dimensional dynamic programming (3DDP) method which includes ship power settings and heading control changes with both time and geographical position. This method aims to minimize fuel consumption in a voyage, also considering safety constraints of the International Maritime Organization (IMO) for the safe operations of all types of merchant ships. Through simulation the author indicates savings up to 3.1 %.

Another approach is through the use of calculus of variations, initially proposed by Haltiner and Hamilton (1962) that minimize time in a static environment where the speed depends on the wave height and direction. Bijlsma (1975) calculates the least time track with the assistance of wave charts and also minimize fuel consumption. Perakis and Papadakis (1989) minimize time using power setting and heading as their control variables. Papadakis and Perakis (1990) developed general methodologies for the minimal time routing problem considering also land obstacles or prohibited sailing regions.

## 4.3 Pathfinding and genetic algorithms

Pathfinding algorithms such as Dijkstra's and A\* have also been applied in weather routing. Padhy et al. (2008) used Dijkstra's algorithm in case studies in the North Indian Ocean, while the A\* has been used by Szlapczynska (2015). Mannarini et al. (2013) present an operational ship routing decision support system that could use meteorological and oceanographic data for environmental factors, and uses a modified version of Dijkstra's algorithm for choosing the optimal route. Simonsen et al. (2015) discuss several algorithms in weather routing, and present their own pathfinding algorithm titled "DIRECT" that minimizes fuel consumption.

Szlapczynska and Smierzchalski (2009) introduced multi-objective approaches in weather routing, and Szlapczynski and Szlapczynska (2012) used evolutionary methods for the multi-ship trajectory

planning problem. Park and Kim (2015) combined the A\* algorithm with a speed scheduling phase problem in order to minimize fuel consumption and achieved reductions between 2 and 3% in their case studies. Bentin et al. (2016) use the A\* algorithm on a bulk carrier and optimize fuel consumption considering also wind-assisted propulsion via Flettner rotors. Other approaches have used genetic algorithms (Veneti et al., 2015; Maki et al., 2011) but these have not been the norm in weather routing. Roh (2013) presents an interesting comparison between the isochrones method and the use of A\*, and concurs that the former has an overall better performance. Larsson and Simonsen (2014) applied the diving rectangles method in the context of weather routing. Finally, Vettor and Guedes Soares (2013) use genetic algorithms to find the Pareto frontier optimizing path and speed at each track between two ports with the multiple objectives being fuel consumption, time of arrival, and risk.

#### 4.4 Artificial Intelligence and Machine Learning

Another emerging research trend is the use of artificial intelligence and machine learning methodologies to improve ship fuel efficiency, predict sailing speeds, and plan optimal routes. Most of the papers in this line of research attempt to use artificial neural networks (ANN) and machine learning methodologies to predict fuel consumption under different sea conditions, in order to optimize voyages with respect to either fuel savings or on-time arrivals. Wang et al. (2016) use a wavelet neural network and develop a real-time energy efficiency optimization model to determine optimal engine speed under different working conditions. In their ship energy efficiency model they account for environmental factors by including wake coefficients and taking into account wind speed and water depth. In ideal cases they report fuel consumption savings of up to 19% per unit distance. Mao et al. (2016) use weather information (wave height, wave period, wind speed) and data on the main engine's RPM for a containership to predict sailing speed with three different statistical models (auto-regression, least square estimates, maximum likelihood method). Such models are helpful in planning routes to ensure arrival on time on voyages and can be incorporated in weather routing problems. Beşikçi et al. (2016) use an ANN to design a decision support system for energy efficient ship operations. They predict fuel consumption using Noon Data and show that the ANN is superior to the use of multiple regression analysis for this purpose. They illustrate savings of up to 165 tons of CO<sub>2</sub> and \$10,470 fuel savings in a hypothetical case study.

Perera and Mo (2016) analyse data from marine engines and identify three engine operating regions which they can use in the ship energy efficiency management plan (SEEMP) to monitor ship navigation taking into account wind conditions during the voyage. Corradu et al (2017) attempt to predict fuel consumption for a tanker vessel and optimize the trim of the vessel considering also

weather conditions that influence this value. They suggest the further use of historical data from vessels for the online selection of the trim to reduce fuel consumption. Du et al. (2019) formulate a ship speed and trim optimization problem over a voyage and utilize two ANN models to predict fuel consumption given the technical specifications of a vessel and the environmental factors (currents, wind, wave). They report fuel consumption savings around 5-8% for two 9,000 TEU vessels through their proposed solutions. Zheng et al. (2019) use an ANN model to predict fuel consumption of a cruise ship and minimize it over voyages in Norwegian waters, noting however that bad weather is assumed not to occur. Their decision variables are essentially the sailing speeds at each leg taking into account also the load of the vessel at each leg. They report savings of up to 11 tonnes in a voyage, which is equivalent to 11%. Gkerekos and Lazakis (2020) use an ANN model to predict the fuel oil consumption of a vessel, and subsequently use a heuristic based on Dijkstra's algorithm to plan the optimal route using the fuel consumption predictions at different points.

#### 4.5 Routing without weather considerations

The last part of this section will present a few application areas that consider an optimal route, without taking weather information into account. These were papers retrieved during our initial search, and we decided to keep them in our review as a complementary source of literature in the overarching voyage optimization theme. These papers focus more on environmental aspects of a voyage, and on cost minimization due to regulations requiring the use of different (more expensive) fuel in certain areas. While these works do not use weather information, further research could be inspired by adding the environmental factors in the problem formulations.

The classical vehicle routing problem (VRP) has been extended to include environmental objectives and a survey from Lin et al. (2014) has revealed a vast literature in the subject on other transportation modes, but no applications in maritime shipping. In recent years several papers have attempted to fill this gap in the field of maritime transportation, and we can consider the "green ship routing" problem as a subset of research in the wider family of ship routing problems. Kontovas (2014) proposes a formulation for the green ship routing and scheduling problem whereby ship air emissions are included in the classic vehicle routing problem (VRP). In his conceptual approach, the author notes the parallels with VRP and considers three alternative approaches. Optimizing with regards to fuel and emissions as objectives with speed as a decision variable, the internalization of external costs of emissions in a total cost minimization problem, or setting a constraint on emissions produced on the VRP formulation. Weather is not taken into consideration in the proposed formulations, but the author stresses the importance of this factor as it can influence the total fuel consumption by a margin

of up to 30%. Meng et al. (2013) review routing and scheduling problems in liner shipping and identify research focusing on emissions, while also noting the effects of weather on fuel consumption. The authors include green shipping in their suggestions for future research directions at the time. Cheaitou and Cariou (2018) consider a multi-objective optimization problem that maximizes profit, and minimizes carbon and sulphur emissions taking sailing speed as a decision variable. The authors also solve a single objective problem by converting emissions into monetary units.

Sulphur emissions minimization objectives have also risen in popularity in academic studies. Minimizing fuel costs does not always translate directly into minimizing emissions. In recent years with the designation of emission control areas (ECA) where there are different fuel requirements (inside ECAs ships are required to burn environmentally friendlier fuel that is more expensive) the ship operator has a financial incentive to reduce speed inside regulated waters and speed up outside (when using cheaper fuel) (Zis et al., 2015). This speed differentiation will lead to increased carbon emissions based on the previous proof, but the total fuel costs may be reduced. Fagerholt and Psaraftis (2015) and Fagerholt et al. (2015) formulated the ECA refraction problem and have shown that there can be an incentive to change the route in order to minimize sailing distance inside regulated waters and trading-off with increased sailing outside ECAs. In this problem as well the total carbon emissions would increase due to the increased sailing distance, but the fuel costs can also be reduced. Sheng et al. (2019) consider the optimal fleet size as an integer decision variable and sailing speeds as continuous decision variables for industrial services affected by ECAs. They relax the integer fleet size and estimate the emissions reductions achieved through the optimal sailing speeds. In their model they do not take into account the effects of weather in the fuel consumption. Chen et al. (2018) focused on the effects of a hypothetical Mediterranean ECA on the Asia-Europe trade routes. Utilizing a discrete choice model they find that a significant portion of the affected fleet would re-route to avoid the ECA, particularly for the smaller vessels. In the aforementioned papers the impact of weather has not been considered in the optimization criteria.

## 5 Taxonomy of ship weather routing papers

Borrowing from the method used in Psaraftis and Kontovas (2013) in their taxonomy of speed models, the previous literature can be classified based on a taxonomy according to the following parameters:

- Optimization criterion: what is the objective of the decision maker (ship operator) and what is to be optimized? These can include time minimization, fuel consumption, risk of passage, or a combination thereof.
- Shipping sector: Is the paper focusing on a specific sector (for example liner, bulk, short sea shipping)?
- Application area: Considers the geography (Atlantic Ocean, Pacific Ocean, shorter passages).
- Solution approach. What is the solution approach and the methods used as these were described in section 3.2?
- Weather data taken into consideration: This may or may not include ocean currents, wind speed, waves, additional oceanographic variables, and even presence of ice in some papers.
- Resolution of data: This considers the spatial resolution of weather data as well as the frequency of updating the weather forecast.
- Ship Fuel efficiency modelling: How is the influence of sailing speeds, draft, trim, and environmental factors (weather and sea conditions) quantified into fuel efficiency?
- Emissions considered: Particularly for research where the objective is to minimize fuel consumption, an additional objective/calculation may involve emissions.
- Size of fleet: Papers that are concerning case studies on a specific vessel on a specified route, or are looking into a more macroscopic perspective with multiple vessels and port calls.
- Type/field: It has been seen that weather routing is an interdisciplinary field, however the papers of the taxonomy are also categorized by the dominant discipline, as well as the document type (journal, conference paper, or thesis).

Based on the aforementioned, we present the taxonomy of 40 indicative works in Tables 5 (a-h) listed in alphabetical order, which is a subset of publications reviewed in this work. We selected a combination of the most cited papers that were published in previous decades, and included some more recent ones when these tackle a new aspect (for example emissions, a proposal of a new algorithm, or using different weather data). It should be stressed that the inclusion of these works in our taxonomy carries a certain degree of subjectivity on our understanding of what constitutes a contribution in the field.



**Table 5a: Taxonomy Part I**

Taxonomy parameter / paper	Armstrong (2013)	Ballou et al. (2008)	Bentin et al. (2016)	Chen (1978)	Delitala et al. (2010)
Optimization Criterion	Review of optimization in low carbon shipping	Fuel consumption	Fuel consumption	Cost	Multi-objective: fuel consumption, arrival, passenger comfort
Shipping Sector	NA	Liner shipping, Bulk, Tanker	Bulk carrier using Flettner rotors	General, case study on barge carrier	Ro-Pax
Application Area	All sectors	Trans-Pacific trans-Atlantic Australia-Japan trans-Alaskan	Trans-Atlantic	Trans-Atlantic	Two Mediterranean routes
Solution Approach	NA	Simulation	Solution algorithm based on A*	Multi-stage dynamic programming	Simulation using commercial software
Weather Data	Wind and wave	Wind and wave	Wind and wave	Wind and wave	Wind and wave
Fuel Efficiency Considers	Speed, wind, wave, trim	Speed, wind, wave, trim	Speed, wave, trim, wind	Wind	NA
Emissions considered	Yes	Yes	No	No	No
Fleet size	One ship	One ship	One ship	One ship	One ship
Type/ field	Journal / Ocean Engineering	Journal/ Ocean Engineering	Conference	PhD Thesis	Journal/ Atmosphere

**Table 5b: Taxonomy Part II**

Taxonomy parameter / paper	Fagerholt et al. (2000)	Grifoll et al. (2018a)	Hagiwara (1989)	Hagiwara and Spaans (1987)	Hinnenthal, and Clauss (2010)
Optimization Criterion	Determine ETA	Operating costs	Minimize time, fuel consumption and cost	Minimize fuel consumption	Multi-objective: fuel consumption, ETA
Shipping Sector	Dry Bulk	Ro-Ro	General, case study on product tanker	Sail assisted tanker	Linershipping
Application Area	Multiple port calls in Baltic, North, and Mediterranean Sea	Mediterranean	North Pacific	Trans-Pacific	North Atlantic
Solution Approach	Solution algorithms based on Dijkstra's	Solution algorithm based on A*	Modified Isochrone method	Modified Isochrone method	Pareto frontier
Weather Data	Avoidance of land masses	Wind speed and wave	Wind, waves oceans and currents provided y FNOC	Wind, waves oceans and currents provided y FNOC	Wind and wave data
Fuel Efficiency Considers	NA	Sailing speed, hull resistance based on data analysis	Speed, weather, trim, treated as inputs. Sail assisted vessels	Speed, weather, trim, treated as inputs. Sail assisted vessels	Sailing speed
Emissions considered	No	No	No	No	No
Fleet size	One ship	One ship	one ship	One ship	One ship
Type/ field	Journal/ Operations Research	Journal/ Transportation	PhD Thesis	Journal/ Navigation	Journal/ Ocean Engineering

**Table 5c: Taxonomy Part III**

Taxonomy parameter / paper	Krata and Szlapczynska (2018)	Kepaptsoglou et al. (2015)	Kobayashi et al. (2011)	Kotovirta et al. (2009)	Kwon (1981)
Optimization Criterion	Fuel cost and safety	Travel time	Fuel consumption	Time, Fuel consumption risk of Ice	Estimate effect of wind and wave on ship speed
Shipping Sector	general cargo, bulker, LNG carrier, liner shipping	Liner shipping in short sea shipping	Liner shipping	Ro-Ro	Tanker, Liner shipping
Application Area	Caribbean Sea	Mediterranean Sea	Trans-Pacific	Baltic Sea	Generic
Solution Approach	Genetic algorithm	Genetic algorithm	Powell method	Simulation	Analytical calculation (Kwon method)
Weather Data	Wind speed and wave	Wind and wave	Currents, wind and wave	Ice, wind, and wave	Wind and wave
Fuel Efficiency Considers	NA	NA	Not explicitly considered. Trade-off with safety	NA	Speed, Wind, wave,
Emissions considered	No	No	No	No	No
Fleet size	One ship	Fleet of small containerships	One ship	One ship	One ship
Type/ field	Journal/ Ocean Engineering	Journal/Transportation	Journal/Navigation	Journal/ Cold environments	PhD/ Ocean Engineering

**Table 5d: Taxonomy Part IV**

Taxonomy parameter / paper	Larsson and Simonsen (2014)	Lin et al. (2013)	Lu et al. (2015)	Maki et al. (2011)	Meng et al. (2016)
Optimization Criterion	Fuel consumption and emissions	ETA and fuel consumption	Fuel Consumption	Multi-objective: Stability, fuel efficiency	Fuel consumption (modelling not optimization)
Shipping Sector	Theoretical	Liner shipping	Tanker	Liner shipping	Liner shipping
Application Area	Theoretical	Transpacific	Transpacific	Transpacific	Asia-Europe and transpacific service
Solution Approach	Sampling algorithm	3D modified isochrones method	Modified Kwon method (empirical)	Genetic algorithm	Regression for Fuel consumption
Weather Data	Theoretical based on Wind, wave (and land avoidance)	Wave and wind data four times a day	Wave, wind, sea direction	Wind and wave	Wave height and wind speed
Fuel Efficiency Considers	Speed, speed loss due to weather, trim, draft	Speed, speed loss due to weather, draft	Based on sailing speed, speed loss due to added resistance	Added resistance due to weather	Regression modelling based on raw shipping logs
Emissions considered	Yes	No	No	No	No
Fleet size	One ship	One ship	One ship at a time (two used)	One ship	One ship at a time
Type/ field	MSc Thesis/ Ocean Engineering	Journal/ Ocean Engineering	Journal/ Ocean Engineering	Journal/ Ocean Engineering	Journal/ Transportation

**Table 5e: Taxonomy Part V**

Taxonomy parameter / paper	Padhy et al. (2008)	Papadakis and Perakis (1990)	Park and Kim (2015)	Perakis and Papadakis (1989)	Perera and Guedes Soares (2017)
Optimization Criterion	sailing time in static sea state	Trajectory avoiding obstacles and restricted areas.	Fuel consumption	voyage time	Risk
Shipping Sector	Theoretical	Theoretical	Liner shipping	Theoretical	Not specific
Application Area	Indian Ocean	Theoretical	2 transpacific case studies	Theoretical	Not specific
Solution Approach	Dynamic programming Dijkstra's	Variational Calculus	A* algorithm and speed scheduling	Variational Calculus	Review paper
Weather Data	Wave data from altimeter records and use of WAM model	No, considers acceptable motions and accelerations for ship	Ocean condition updated four times a day	No, considers avoiding storms	Wave wind and tidal currents
Fuel Efficiency Considers	NA	NA	Speed loss due to environmental factors	NA	Approximated cubic relationship with speed
Emissions considered	No	No	No	No	No
Fleet size	One ship	Theoretical for one ship	One ship	Theoretical for one ship multiple destinations	Not specified
Type/ field	Journal Article/ Ocean Engineering	Journal Article / Operations Research	Journal/ Ocean Engineering	Journal Article / Operations Research	Journal/ Ocean Engineering

**Table 5f: Taxonomy Part VI**

Taxonomy parameter / paper	Prpić-Oršić et al. (2015)	Roh (2013)	Shao and Zhou (2011)	Shao et al. (2012)	Sidoti et al. (2017)
Optimization Criterion	Fuel consumption and CO <sub>2</sub>	Fuel consumption and costs	Fuel consumption and CO <sub>2</sub>	Fuel consumption	Multi-objective fuel consumption / time
Shipping Sector	Linershipping	Application on Very Large Crude Carrier	Liner shipping	Liner shipping	Theoretical
Application Area	Trans-Atlantic	(Taiwan – Korea) (Seattle – Hawaii) (Japan – USA)	North Atlantic	North Atlantic	Theoretical case study Virginia (USA) to Haiti
Solution Approach	Analytical calculation	Modified isochrones method	Dynamic programming (three-dimensional)	Dynamic programming ( 3D recursive forward)	Multi-objective dynamic programming
Weather Data	Wave wind and sea level data	Static case, using Beaufort number as input	Weather forecast provided by NOAA	Wave height and wind speed, avoid storm	Wave and wind data
Fuel Efficiency Considers	Speed loss due to weather	Increased resistance and speed loss (trim, draft environmental factors)	Ship speed, loss of speed at rough weather (Kwon’s method)	Ship speed, loss of speed at rough weather	Environmental factors including temperature
Emissions considered	Yes	No	Yes	No	No
Fleet size	One ship	One ship	One ship	One ship	One ship
Type/ field	Conference/ Ocean Engineering	Journal / Ocean Engineering	Conference / Ocean Engineering	Journal / Ocean Engineering	Journal / Operations Research

Table 5g: Taxonomy Part VII

Taxonomy parameter / paper	Szlapczynska (2014)	Takashima et al. (2009)	Varelas et al. (2013)	Veneti et al. (2015)	Vettor and Guedes Soares (2016)
Optimization Criterion	Multi-objective formulation on fuel consumption, time, and avoidance of unsecure areas	Fuel consumption	time and fuel consumption	Total time, Fuel cost, and risk	time and fuel consumption
Shipping Sector	Ship type not specified	Ro-Ro and bulk carrier	Bulk carrier	Not specific	Liner shipping Fishing vessel
Application Area	North Atlantic	Japan	Trans-Atlantic	Aegean Sea	Transatlantic Mediterranean
Solution Approach	Evolutionary algorithm	Dynamic programming, Dijkstra's	Dynamic Programming	Genetic algorithm	Multi-objective evolutionary algorithm
Weather Data	Waves, currents, tides, piracy and extreme wind areas	Wind and wave	Wave and wind	Wind speed and wave	Waves and weather conditions
Fuel Efficiency Considers	Calculated considering weather conditions	Increased resistance and speed loss	Increased resistance and speed loss (trim, draft environmental factors)	Increased resistance based on wind and wave	Weather conditions
Emissions considered	No	No	No	No	Yes
Fleet size	One ship	One ship	One ship	One ship	One ship
Type/ field	Journal / Navigation	Journal/ Navigation	Journal/Operations Research	Conference/ Transportation	Journal / Ocean Engineering

**Table 5h: Taxonomy Part VIII**

Taxonomy parameter / paper	Walther et al. (2016)	Wang et al. (2018)	Wei and Zhou (2012)	Windeck (2013)	Zaccone et al. (2018)
Optimization Criterion	Fuel consumption, voyage time	Fuel consumption modelling	Fuel consumption	Fuel consumption and costs	Minimize fuel consumption and risk
Shipping Sector	Not specific	Linershipping	Not specific	Liner shipping	Bulk carrier
Application Area	Not specific	global	Not specific	North Atlantic and gulf of Mexico	North Atlantic
Solution Approach	Review of different methods	LASSO Regression	3D- Dynamic programming	Multi-objective label setting algorithm	Forward 3D dynamic programming
Weather Data	Wave data	Wind direction	Wind and wave	Wind and wave data provided by the German governmental weather services	Waves and wind based on National Weather Service four times a day
Fuel Efficiency Considers	NA	LASSO Regression modelling based on ship reports	Increased resistance based on wind and wave	Speed, weather, trim, treated as inputs. Kite propulsion force	Added resistance due to wind and waves
Emissions considered	No	Input in the training model	No	Yes	Yes
Fleet size	NA	884 voyages of 97 ships	One ship	One ship at each case study	One ship
Type/ field	Journal/ Navigation	Journal/Transportation	Journal/ Navigation	Book/ Operations Research	Journal / Ocean Engineering



## 6 Discussion and further research directions

This paper has provided a survey on weather routing, environmental routing and voyage optimization research in recent years. It has additionally provided a brief summary on wind and wave resistance calculations for sailing ships taking into account environmental factors in order to estimate power prediction and subsequently fuel consumption. In the following we will highlight some topics that future research could look into. In a sense, advances on such topics could help overcome some of the limitations in the current research we have reviewed.

### 6.1 Big data and increased computational power

The main methods in optimizing a route given the environmental factors have not changed significantly throughout the years. The majority of research has used a combination of the modified isochrones method and dynamic programming, occasionally using heuristics for determining the optimal path. In the earlier years the weather routing consisted of simply avoiding areas with big storms, but more complicated objectives have been introduced throughout the years. Currently there is better information on weather forecasts, with much higher spatial and temporal resolution. The improvement in data quality and availability may facilitate the development of online algorithms for the optimal path in a voyage. Since the introduction of the Automatic Identification System (AIS), there are vast data on the sailing speed and position of ships globally. AIS data can be particularly useful to illustrate when ships deviate due to weather from traditional routes, and also provide real information on the actual benefits achieved through weather routing particularly as regards savings in total voyage time. In transportation research such big data are being used with machine learning techniques to provide better insights on the prediction of short term traffic. Kang et al. (2018) use AIS data to estimate ship traffic in the Singapore Strait and estimate its theoretical capacity. At the same time, big data in weather forecast have been used to improve their accuracy. However, in the more narrow area of maritime weather routing this has not been the case. The accuracy of weather forecasts for a sufficient prediction period is a necessary requirement to operate vessels efficiently (Hagiwara and Spaans, 1987), and although it is improving there will always be uncertainties. Robust optimization models have been used to deal with the uncertainty of fuel consumption rates as a consequence of weather uncertainty (Du et al., 2015). Apart from robust optimization, there is a growing research trend on the use of machine learning models for the prediction of fuel consumption and the impacts of weather on fuel economy. We note the

paper of Lee et al. (2018) that uses data mining to identify weather impacts on given voyages. In maritime shipping Yoo and Kim (2016) proposed a path planning algorithm using machine learning and manage reductions of up to 22% in travel time. Another line of research could assess the benefits of an improved current forecast via satellite altimetry where optimal routes could be compared with weather routing using standard current forecasts. Finally, the use of advanced statistical methods and ANN in predicting sailing speed given the environmental conditions of a voyage has seen an uptake in recent years. These methods may help refine the optimal path and trim for voyages and thus improve the benefits of weather routing.

## 6.2 A need to standardize the reporting of achieved results

While computing power and weather information data availability is increasing, the main methodologies used in the field of ship weather routing have not changed significantly. For most of the reviewed studies the objective had been to either minimize fuel consumption or sailing time (or occasionally both in multi-objective formulations). An important observation is that different studies tend to show a wide range of achieved savings when their suggested methodology is used. In that regard, it might be difficult to compare these methods. Perhaps the weather routing community could benefit by a standardization of what constitutes a saving. In several papers actual fuel savings are either not reported, or presented as percentages without specifying what is the baseline case (for example a worst case scenario where the ship is caught in extreme weather, vs the average fuel consumption reported by the ship operator considering many trips). This might explain why in some papers the savings exceed 15%, when the majority (of even the commercial solutions) report savings in the range of 3 to 5%. Furthermore, due to the very large differences of shipping sectors (short sea shipping vs ocean going vessels), sailing speeds of different ship types, environmental factors (currents, streams etc.), the savings will also be greatly different. Ideally, some benchmarking instances could be produced to facilitate future researchers in this field. For example providing data on a specific ship, on a voyage where weather information is known (actual weather), and the methodologies could then compare their findings when using the weather prediction (historical data) for the same trip, vs the reported fuel consumption in the actual trip, and vs the theoretical optimal if the full weather conditions were known and not based on a forecast. In addition, sensitivity analyses on the impact of data frequency and density can also help future research. This could be straightforward to implement by running the algorithm when for example weather forecast data is updated every 3,6, or 12 hours. On the issue of data density, it would make an interesting

comparison to see fuel or time savings when the weather forecast resolution is changing as well.

### 6.3 Impacts of regulation

It is expected that in the next years the pressure to reduce the environmental impacts of shipping will be increased. According to the third IMO greenhouse gas study (IMO, 2014), total CO<sub>2</sub> produced by international shipping in 2012 was 796 million MT. An average 1% savings in fuel consumption due to better routing by the world fleet would translate into a global reduction of about 8 million MT of CO<sub>2</sub> per year. Whether this takes the form of a commitment to cut greenhouse gas (GHG) emissions by at least 50% as targeted by the IMO in the context of its “Initial IMO Strategy” (IMO, 2018a), or a different target is set, it is certain that technological, logistical, and policy measures will be required to meet these goals. Weather routing has been shown to be successful in saving fuel regardless of the shipping sector and geographical areas. At the IMO, discussion on speed optimization as a candidate short term measure (Psaraftis, 2019) has elevated the role of weather routing as one of the tools to optimize ship speed at the operational level. At the same time, there are several proponents of introducing speed limits as a means to reach these goals (and the expected longer voyages would be more susceptible if caught in bad weather). It has been argued that the adoption of the Energy Efficiency Design Index (EEDI) may in some instances turn problematic (Lindstad et al., 2019) as (a) it could lead into underpowered ships to secure compliance and (b) it only refers to the performance of the ship in calm water. This would constitute optimal weather routing a matter of paramount importance. Finally, regulations such as the ECAs have introduced new routing problems due to the potential for speed optimization in different legs and different geographical areas. If newer regulation comes in place that regulates the environmental performance of ships taking also weather information into account, or in specific waters (or for example near coastlines), new research questions will arise.

### 6.4 Autonomous vessels and virtual arrival

Another emerging field in the maritime sector is the design and use of autonomous vessels. The IMO (2018b) produced a report on a regulatory scoping exercise surveying the views of maritime professionals on autonomous shipping. The report shows that several respondents raised concerns on safety of autonomous vessels, particularly on avoiding collisions with smaller vessels in bad weather conditions. Therefore an extension of weather routing models could be looking into this area as well in areas of high traffic. In addition, the European

Commission has funded research projects in the area (see project MUNIN - Maritime Unmanned navigation through Intelligence in Networks). The project developed routing algorithms for avoidance of ships and areas of severe weather. Similar research is already undertaken in Japan with the intention of launching self-navigating ships by 2025 using artificial intelligence driven steering systems to plan fuel efficient, safe, and shortest routes. The 100<sup>th</sup> Session of the Maritime Safety Committee (MSC, 2018) of the IMO considered four different levels of vessel autonomy envisioned, starting with a) provision of support on-board through some automated operations, b) remotely controlling a ship with seafarers on-board, c) remotely controlling a vessel without seafarers, d) a fully autonomous vessel capable of making decisions by itself. Lloyd's register (2017) considers six levels as a) an on-board decision support system with actions taken from a human operator, b) on & off decision support where data may also be provided by systems off-board, c) active human in the loop that supervises decisions and actions, d) human on the loop that supervises autonomous actions, e) fully autonomous with decisions made and actioned by the system with rare supervision, and finally f) unsupervised operation throughout a mission. A fully autonomous vessel will allow significantly lower sailing speeds as there would be no negative impacts on crew in extremely long voyages. Such voyages that would not be constrained on their actual duration, would have a different optimal route by for example relying more on using currents for their propulsion and further reducing fuel consumption. At the same time, an autonomous vessel could limit occurrences with very high sailing speeds in the beginning of the voyage to have a buffer and slow down at the later stages. The Virtual Arrival concept can also be examined from the ship operator's perspective, where if the weather forecast shows that there would be a delay, then the ship operator could negotiate with the port authority for a later time window of arrival. Similarly, a port authority may monitor incoming ships and based on weather routing algorithms deduce that a specific vessel would not be able to arrive on time. The port could issue a command to different vessels to speed up in order to ensure a high berth occupancy.

## 6.5 Concluding remarks

Weather routing is not a new concept but it has seen a rapidly increasing attention from academics and practitioners in recent years. We expect that the fields of weather routing and voyage optimization will maintain the current momentum and keep attracting research interest in the future. These are very interdisciplinary fields as evidenced by the wide spectrum of publication outlets, developed methodologies, as well as applications found in the literature. This paper aimed to summarize the main methodological approaches found in the literature and

provide a critical review of important papers published in these fields. The paper constructed a taxonomy that classified relevant papers based on key parameters, and identified certain promising research trends for follow up research. It can therefore be useful for new researchers entering the field and seeking to understand better the status quo and research gaps that require addressing. Weather routing will play an important role in achieving the GHG emissions reduction requirements of the initial IMO strategy. The improved weather forecasts, data availability, and increased computational power paves the way for more applied research in voyage optimization.

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