Weather routing for a wind driven hybrid merchant vessel

Laura Walther
Carlos Jahn
Fraunhofer Center for
Maritime Logistics and Services CML
Am Schwarzenberg-Campus 4
21073 Hamburg, Germany

Terje Lade
Lade AS
Gange Rolvs gate 7
6005 Ålesund, Norway

***Abstract*—Competetion and constant cost pressure as well as introduced emission regulations pose challenges for shipping companies. The wind driven hybrid merchant vessel concept Vindskip™ presents an innovative approach to ensure sustainable sea transport. Due to its hull shaped like a symmetrical air foil above the waterline an aerodynnamic lift is generated acting as a propulsive force. In order to utilize the available wind energy during each voyage as efficiently as possible Vindskip™ requires a customized weather routing module. This paper describes its development in line with the specific requirements of Vindskip™.**

***Index Terms*—Vehicle routing, weather routing, voyage optimization, optimal scheduling, wind energy, wind driven ship.**

I. Introduction

Fuel costs account for a major percentage of costs in the shipping industry. Taking high prices for fuel as well as emission regulations into account, it is of significant importance to improve a ship's fuel economy to ensure cost efficiency and sustainable sea transport. An innovative concept to meet tomorrow's demands regarding fuel economy as well as emission control is the project Vindskip™, illustrated in Fig. 1. The ship's main particulars are summarized in Table I. The hybrid merchant vessel concept that is equipped with an electric propulsion system using liquefied natural gas (LNG) has been developed by the company Lade AS. The concept is based on utilizing wind for propulsion by a unique hull shape above as well as below the waterline. The vessel's hull is shaped like a symmetrical air foil above the waterline. The relative wind generates an aerodynamic lift, and thus a pull within an angular sector of the ship's direction. Due to the combination of wind and LNG instead of heavy fuel oil, the fuel consumption is estimated at only 60 % of a reference ship's consumption on average. A reduction of carbone dioxide emissions of 80 % can be achieved, according to rough calculations by Lade AS. In order to utilize winds favorable for propulsion during each deep sea voyage of the Vindskip™ a weather routing module is required to calculate the best sailing route under consideration of the wind-induced propulsion.

State-of-the-art weather routing systems have been analyzed in [1]. The systems differ with regards to the consideration of local and global weather forecasts, ensemble forecasts, the ship's seakeeping behavior and stability data, motion sensor and wave radar data, route restrictions and provided interfaces. These aspects as well as the implemented optimization algorithm influence the quality of the optimized route. The results of this elaboration are endorsed by [2] highlighting that most systems are only capable of optimizing the ship's heading but not its speed due to the used optimization method. However, a superior weather routing system should include route and speed optimization to provide sound voyage optimization. In reference to Vindskip™, it addtionally needs to precisely consider particularly the specific aerodynamic data. Thus, this paper describes the development of a customized weather routing module for Vindskip™.

Fig. 1. Vindskip™

TABLE I
SHIP CHARACTERISTICS

Characteristics	Symbol	Value
Type	-	Car Carrier
Length between perpendiculars	L_{pp}	200 m
Breadth	B	49 m
Depth	D	36 m
Air draught	H	47 m
Draught	T	9.5 m
Service speed	v_S	19.0 kn
Displacement volume	∇	26000 m^3

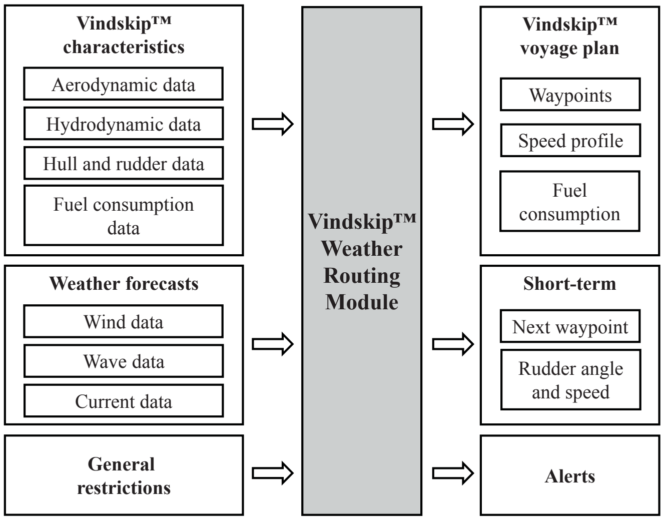


Fig. 2. Scope of the Vindskip™ Weather Routing Module

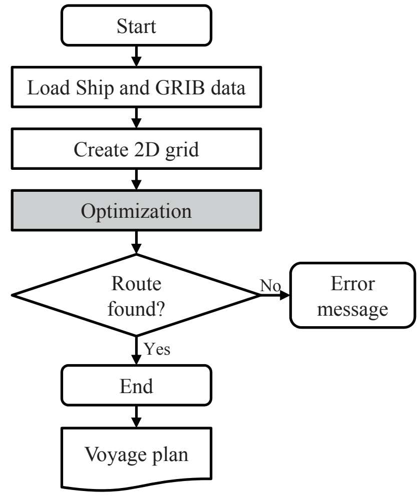


Fig. 3. Approach of the Vindskip™ Weather Routing Module

II. Scope of the module

The scope of the Vindskip™ Weather Routing Module is defined on the basis of general standards of weather routing systems in combination with the specific requirements of Vindskip™. It is developed in analogy to the scope defined for an autonomous vessel in [1]. The module needs to account for the innovative design of Vindskip™ to use the aerodynamic lift generated by the wind as propulsive force most efficiently. Thus, the module has to consider the ship's characteristics, mainly aero- and hydrodynamic data but also hull, rudder and fuel consumption data as outlined in Fig. 2. Great importance is furthermore attached to the analysis of combined meteorological and oceanographic (metocean) forecasts including the strength and direction of wind, waves, and current in the area within the ship's range during the forecast period. The route is aimed to be optimized with regards to the fuel consumption under consideration of defined restrictions. Restrictions are related to the ship's safety, the voyage duration, thus the latest possible estimated time of arrival and routing restrictions. The module's output data needs to be a voyage plan including waypoints, speed profile and total fuel consumption of the route. As to short-term operation the next waypoint, the according rudder angle and speed shall be presented as well as alerts related to deviations between the actual and calculated voyage data.

III. Concept

The defined scope of the module illustrates the problem of finding the path with the lowest fuel costs from the departure location to the destination, while avoiding obstacles. Variables are the geographical position of the next waypoint, or the heading towards it, as well as the time at this waypoint, or the ship's speed between waypoints respectively. The approach to address the described problem, the optimization algorithm forming its basis as well as the architecure to determine the costs at each waypoint to optimize route and speed are elaborated in this section.

A. Approach

The weather routing problem faced by Vindskip™ represents a pathfinding problem. In most state-of-the-art weather routing systems the problem is approached by variations of Dijkstra's algorithm, as to [2]. A widespread method is the A* algorithm. However, deficits are said to refer to the negligence of speed management, which is essential for safe and efficient voyage optimization [2]. It allows the ship to react amongst others to engine overloading or to slow down in severe weather conditions and thereby reduce risk and increase safety. Moreover, it enables the ship to adjust its speed in agreement with favorable wind conditions, which is essential to exploit the potential for fuel savings of Vindskip™. Nevertheless, the Vindskip™ Weather Routing Module uses the A* algorithm to find an optimum route with favorable wind angles to maximize the effect of the Vindskip™ design. The extension in the temporal domain allows the optimization of the ship's speed. The tool consequently combines route and speed optimization to provide sound voyage optimization. The module is based on the analysis of metocean weather forecasts provided as GRIB data, thus GRIdded Binary or General Regularly-distributed Information in Binary form. This mathematically concise data format is a common way in meteorology to store weather data forecasted for each node of a grid. The A* algorithm works on a graph, thus a set of vertices with edges connecting them. Taking into account the GRIB data a 2D grid can be created, as to Fig. 3, that represents the set of vertices required for the optimization. In case that a route is found under consideration of the given input data and restrictions the calculation is finished, otherwise an error message is displayed.

B. Optimization algorithm

The A* algorithm applied in the weather routing module has the objective to optimize a route regarding minimum fuel costs. As the costs correlate with the fuel consumption the target function aims to minimize the fuel consumption per voyage. Therefore, it combines the exact fuel cost $G(k)$ of the path from the departure location to any vertex k with the heuristic estimated fuel cost $H(k)$ from this vertex to the destination. Thus, for every vertex k the function $F(k)$ is an estimation of the costs from the starting vertex to the destination vertex via the vertex k as expressed in Eqn. (1):

$$F(k) = G(k) + H(k) \leq min\{G(i) + H(i) \mid i \in B\} \quad (1)$$

Here, B is a set of vertices that have not been used on the path from the start to vertex k [3]. A* balances $G(k)$ and $H(k)$ as it moves from the start to the destination. Each time through the main loop, the algorithm determines the vertex k that has the lowest estimated costs $F(k)$. At the start $G(Start)$ equals zero, while $H(Start)$ is equal to the minimum estimated costs from start to destination. At the destination, in contrast, $H(Destination)$ is equal to zero and $G(Destination)$ amounts to the exact costs from start to destination. The architecture to calculate the exact costs $G(k)$ at every vertex k or every waypoint is explained in the next section.

C. Architecture

In order to calculate the optimum route with the lowest fuel consumption, waypoints need to be constantly added to the path starting from the departure location. To determine the next waypoint and add it to the route all directly adjoining nodes of the grid, thus the neighbors of the current waypoint, are analyzed with respect to costs. The neighbor with the lowest estimated costs $F(Neighbor)$ is the next waypoint. As long as the destination is not reached, the maximum available time has not elapsed and there are vertices available to be considered as next waypoint, waypoints are added to the path. The value of the total estimated costs $F(k)$ mainly depends on the complexity to calculate the exact costs $G(k)$. The architecture to calculate the exact costs $G(k)$ at every vertex k or every neighbor of a waypoint is illustrated in Fig. 4. The calculation is based on two variables, the ship's heading α_G between the current waypoint and the considered neighbor as well as the ship's ground speed v_G between the two points taking into account a defined minimum and maximum speed as well the time available to travel the distance. The effect of the current provided in the weather forecasts leads to the ship's speed v_S and heading α_S through the water. Furthermore, the true wind speed v_T and direction γ can be derived from the weather forecast data related to wind and current. The effect of current is described in Section IV-A. The effect of the true wind on the ship's hull results in the apparent wind speed v_A and angle β, which is described in greater detail in Section IV-B. Considering the apparent wind, wave data from the weather forecasts and its influence on the ship as outlined in Section IV-C, as well as the ship's hull and rudder data, its aerodynamic and hydrodynamic data the total drag D can be derived, as explained in Section V. As a last step to derive the exact costs at the neighbor the required shaft power P_D and

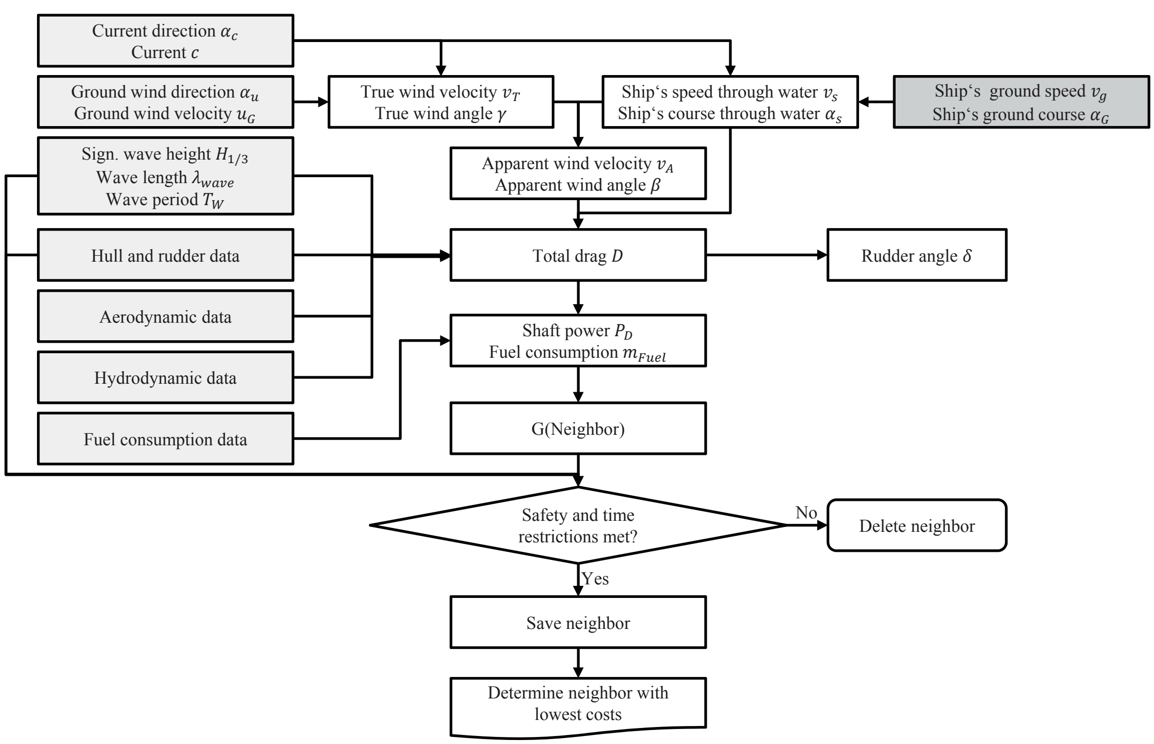


Fig. 4. Architecture to determine exact costs at each neighbor

the fuel consumption m_{Fuel} need to be calculated based on the total drag and the ship's fuel consumption data. The exact costs at the neighbor $G(Neighbor)$ are then equal to the sum of the calculated fuel costs and the exact costs $G(Waypoint)$ at the current waypoint. If the defined safety requirements (see Section IV-C) as well as the time restrictions are met the neighbor is saved as potential next waypoint. Otherwise it is not taken into account as next waypoint. The neighbor with the lowest estimated fuel costs $F(Neighbor)$ is added to the route as next waypoint. According to this procedure the route with the lowest fuel consumption with respect to the ship's data, the weather forecasts and defined restrictions is derived.

IV. Influence of environmental conditions

The Vindskip™ Weather Routing Module considers the influence of wind, waves and current as environmental conditions. The environmental data is derived from metocean weather forecasts, which are provided as GRIB data.

A. Influence of current

In a geographically fixed reference frame, which is relevant for navigation, the current is a translatory motion of the system "ship" and its aero-hydrodynamics against the ground. Thus, the current velocity c is the water flow against the ground. As it has impact on the true wind velocity v_T, the relation in Eqn. (2) between the true wind velocity v_T and the geographic or ground wind u_G, provided by weather forecasts, needs to be considered. The ship's speed over ground v_G in Eqn. (3) equivalently depends on the current c and the ship's speed v_S through water. The time t_k in Eqn. (4) at the next vertex k is based on the time at the previous or parent vertex t_p as well as the distance between these two vertices d_{pk} and the speed over ground v_G.

$$v_T = u_G - c \tag{2}$$

$$v_G = v_S + c \tag{3}$$

$$t_k = t_p + \frac{d_{pk}}{v_{G,k}} \tag{4}$$

B. Influence of wind

In order to consider the effect of the wind the concept of apparent wind, shown in Fig. 5, can be applied to Vindskip™. In line with Fig. 5, Eqn. (5) and (6) are used to derive the apparent wind velocity v_A and its angle of attack β. The angle of attack is defined as the angle between the center line of the ship and the vector of the apparent wind velocity v_A. The apparent wind velocity can be calculated based on the true wind velocity v_T, the ship's speed v_S and the angle γ between the ship's center line and the true wind vector.

$$v_A = \sqrt{v_S^2 + v_T^2 + 2v_S v_T cos(\gamma)} \tag{5}$$

$$\beta = tan^{-1}\left(\frac{v_T sin(\gamma)}{v_S + v_T cos(\gamma)}\right) \tag{6}$$

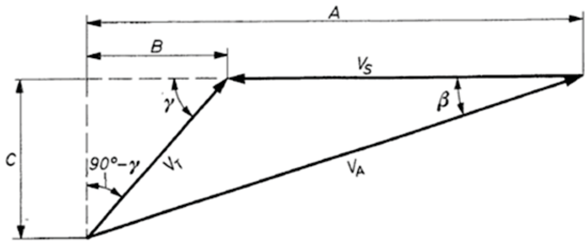


Fig. 5. Concept of apparent wind [4]

C. Influence of waves

The influence of waves is crucial with regards to two aspects, the added resistance of a ship in a seaway and the ship's safety. In general, the used GRIB data includes information on the significant wave height, the mean wave length and its direction. The ship's added resistance due to waves can be taken into account as a function of the ship's speed and angle of encounter. In addition to the still water resistance it is considered in the weather routing module as component of the total drag. The higher the drag the greater is the required shaft power leading to an increase of the fuel consumption.

With respect to the ship's safety the International Maritime Organization (IMO) has published guidelines applicable to all types of merchant ships to avoid dangerous situations in adverse weather and sea conditions considering wind induced waves and heavy swell by defining minimum safety requirements in MSC.1/Circ. 1228 [6]. Critical phenomena relate to surf-riding and broaching-to, reduction of intact stability when riding a wave crest amidships, synchronous rolling motion and parametric roll motion. Phenomena such as slamming, shallow water effects, or collision and stranding risks, however, are not included [6].The pitch and roll motions as well as accelerations are of special interest. In order to apply the guidance published by IMO in [6] particularly the ship's natural period of roll T_R in seconds is crucial. This depends on the loading condition and the metacentric height of the ship, which needs to be part of the ship data. Countermeasures proposed by IMO to avoid critical zones related to dangerous weather situations mainly refer to speed and course alterations. Generally, it is recommended to reduce the ship's speed, which, though, should not fall below a minimum speed to maintain course control [5]. Anyways, only a very rough indication of dangerous situations is given by applying the guidance. Deficiencies clearly refer to its limited applicability to innovative ship designs and the fact that critical phenomena might occur in situations not covered by IMO as well as in situations considered to be rather safe. Nevertheless, the application of the guidance [6] shall be optional in the weather routing module. This at least gives the possibility to roughly check if critical weather phenomena are likely to occur during a voyage.

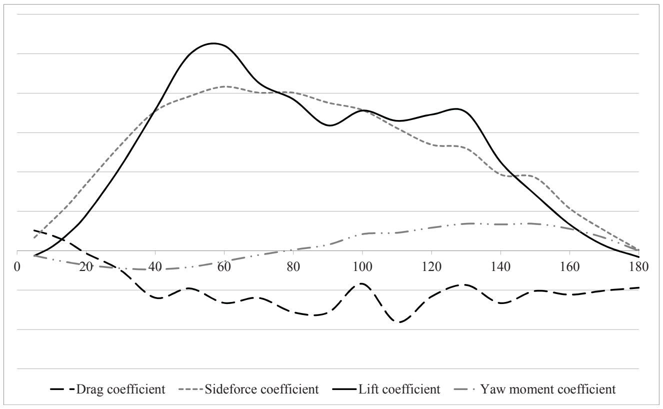


Fig. 6. Aerodynamic forces and moments of Vindskip™

V. Calculation of forces and moments at the hull

The aerodynamic forces and moments acting on the ship's hull are induced by the apparent wind. They are derived using data from wind tunnel tests providing the aerodynamic forces and moments as a function of both apparent wind speed and angle. The curves of the aerodynamic drag, sideforce, lift and yaw moment coefficients are displayed in Fig. 6. It can be seen that maximum effect of the ship's hull can be achieved at apparent wind angles between crosswind and headwind. The hydrodynamic sideforce Y, yaw moment N and drag D are available as functions of the yaw angle β_H and the rudder angle δ_R as expressed respectively in Eqn. (7), (8) and (9). The equations have been derived on the basis of the aerodynamic data gained from the tests in the wind tunnel as well as calculations using computational fluid dynamics. As the hydrodynamic sideforce and yaw moment need to be balanced with the aerodynamic sideforce and yaw moment, the according yaw angle and rudder angle can be derived by solving the system of equations. Using the yaw and the rudder angle the hydrodynamic drag, thus the calm-water resistance, can be calculated using Eqn. (9). It is required for further calculations of the required shaft power and fuel consumption.

$$\begin{aligned} Y(\beta_H, \delta_R) \quad = \quad & a_{00} + a_{10}\beta_H + a_{01}\delta_R \\ & + a_{20}\beta_H^2 + a_{11}\beta_H\delta_R + a_{02}\delta_R^2 \\ & + a_{21}\beta_H^2\delta_R + a_{12}\beta_H\delta_R^2 + a_{03}\delta_R^3 \end{aligned} \tag{7}$$

$$\begin{aligned} N(\beta_H, \delta_R) \quad = \quad & b_{00} + b_{10}\beta_H + b_{01}\delta_R \\ & + b_{20}\beta_H^2 + b_{11}\beta_H\delta_R + b_{02}\delta_R^2 \\ & + b_{21}\beta_H^2\delta_R + b_{12}\beta_H\delta_R^2 + b_{03}\delta_R^3 \end{aligned} \tag{8}$$

$$\begin{aligned} D(\beta_H, \delta_R) \quad = \quad & c_{00} + c_{10}\beta_H + c_{01}\delta_R \\ & + c_{20}\beta_H^2 + c_{11}\beta_H\delta_R + c_{02}\delta_R^2 \\ & + c_{21}\beta_H^2\delta_R + c_{12}\beta_H\delta_R^2 + c_{03}\delta_R^3 \end{aligned} \tag{9}$$

VI. Calculation of fuel consumption

The propulsion unit proposed for Vindskip™ is based on gas fuelled power and propulsion. Evaluating and comparing different potential operating modes it can be concluded that *Mechanical power-take-off* is the most efficient mode of operation as long as the propulsion power is below approximately 4500 kW, whereas *Mechanical power-take-in* is the choice for a propulsion power above 4500 kW. In this case, however, the fuel consumption increases due to the start of the second auxiliary engine. The fuel consumption as a function of shaft power for both operational modes is used as a basis for the fuel consumption calculation in the weather routing module. The shaft power can be derived from the ship's speed v_S, the total drag D and the propulsion efficiency η_D as in Eqn. (10). The calculated shaft power P_D, the according specific fuel consumption $b_{e,Fuel}$ and the time required to reach the next waypoint t_{pk} provide the basis for the absolute fuel consumption m_{Fuel} using Eqn. (11). The costs are then estimated based on the current price per ton of LNG.

$$P_D = \frac{D \cdot v_S}{\eta_D} \tag{10}$$

$$m_{Fuel} = P_D \cdot b_{e,Fuel} \cdot t_{pk} \tag{11}$$

VII. Output data

The output can be categorized in three main groups, data related to the voyage plan, short-term information and alerts. The voyage plan comprises waypoints, a speed profile, the total fuel consumption and resulting costs for the complete route under consideration of the available weather forecasts, as indicated in Fig. 2. The route plan is given in the IEC 61174 industry standard for route exchange format [7], which allows an import into an Electronic Chart Display and Information System (ECDIS).

Short-term information within the range of the most accurately available weather forecasts includes rudder angle, speed, thus propeller revolutions, and the very next waypoints. In addition, the weather information can be monitored to analyze deviations related to the present and forecasted weather, the actual and calculated track as well as the actual and optimal wind direction. A crew is notified by an alert in case a signifant deviation is detected. Thereby, assistance is provided to the crew on-board Vindskip™ in order to ensure a safe and efficient voyage.

VIII. Scenario testing

A widespread area of application of weather routing systems are transatlantic voyages. Here, the route is rather simple without many obstacles such as islands. This allows many potential routes, amongst others a northern or southern route. As to [2] higher uncertainty regarding on-time-arrival but also a lower fuel consumption are attributes of a short northern route, while a longer southern route is characterized by a lower uncertainty and higher consumption. In the case of Vindskip™ particularly the wind speed during its voyage is of interest for

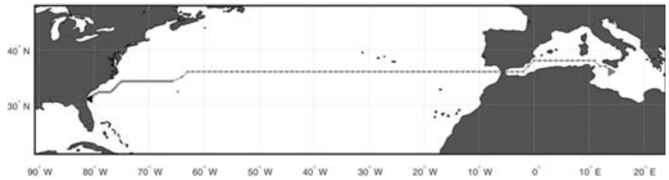


Fig. 7. Route of Vindskip™ from Jacksonville to Valetta

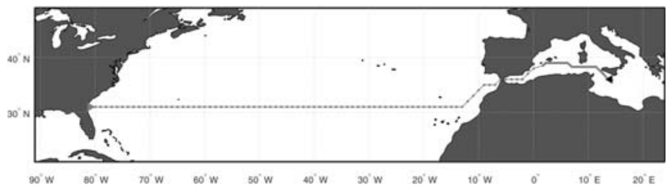
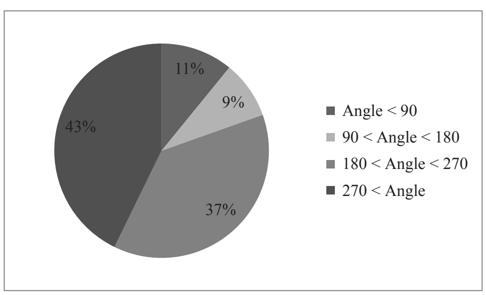


Fig. 8. Route of Vindskip™ from Valetta to Jacksonville

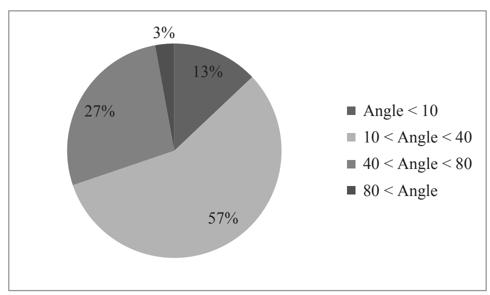
the ship's performance and fuel consumption, thus for a fuel-minimized route. A route that has been taken into account for previous estimations by Lade AS is the one from Jacksonville (Florida, U.S.) to Valetta (Malta). This is also used for the tests addressed in this paper as well the route from Valetta to Jacksonville. Weather forecasts for December 2013 when depression "Bernd" was developing in the northern hemisphere are provided by Germany's National Meteorological Service, the Deutscher Wetterdienst (DWD), and are used as a basis for the tests. As the center of interest for Vindskip™ refers to favorable wind conditions along the caluculated route, the evaluation of the test results is focused on the wind conditions.

The calculated route from Jacksonville to Valetta is visualized in Fig. 7, while the opposite direction is shown in Fig. 8. It can be seen that slightly different routes are chosen for both voyages, which are both close to the direct route. For the route from Jacksonville to Valetta the distribution of the absolute wind direction is shown in Fig. 9a. It indicates that the ship heading east faces wind directions between 180° and 270° for 37 % and between 270° and 360° for 42 % of the voyage, while directions between 0° and 180° only account for 20 %. This distributions in combination with the wind speed, the ship's speed and its heading lead to the apparent wind angles in Fig. 9b. It can be concluded from the figure that the ship faces favorable apparent wind angles between 10° and 80° for 84 % of the voyage as to Fig. 6. Thus, the occurance of disadvantageous wind conditions is minimized on this route.

The route from Valetta to Jacksonville is characterized by the ship experiencing different weather conditions than on the previously assessed route according to the development of despression "Bernd" and other weather phenomena. It can be seen from Fig. 8 that a route slightly further south is derived. The distribution of the absolute wind direction along this route is displayed in Fig. 10a. As the ship heads in western direction and the share of the absolute wind direction amounts to 35 % for 0° to 90° and 39 % for 90° to 180° the ship mainly experiences winds between headwind and crosswind. Taking into account the wind speed, the ship's speed and heading according to the concept of apparent wind, the distribution of the apparent wind angle shown in Fig. 10b is derived. On this route, the ship faces a higher percentage of unfavorable

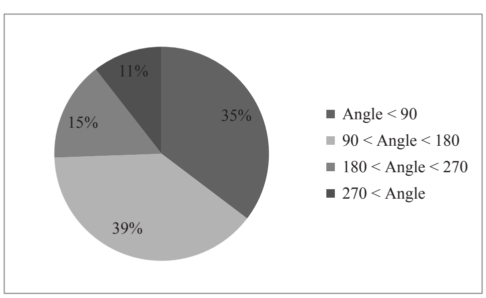


(a) Absolute wind direction

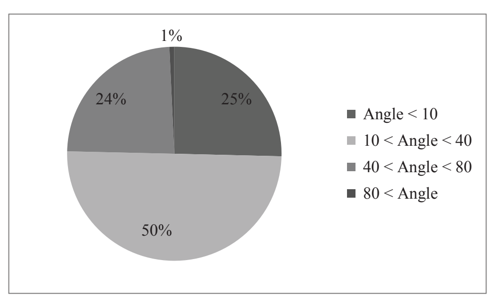


(b) Apparent wind angle

Fig. 9. Route from Jacksonville to Valetta



(a) Absolute wind direction



(b) Apparent wind angle

Fig. 10. Route from Valetta to Jacksonville

conditions as the apprent wind angle amounts to values below 10° for 25 % of the voyage. However, a percentage of 74 % for an apparent wind angle between 10° and 80° leads to the conclusion that favorable wind conditions are exploited as efficiently as possible on this route as well.

IX. Conclusion

With the Vindskip™ Weather Routing Module described in this paper an assistance system has been developed to account for the innovative approach of Vindskip™ to use the aerodynamic lift generated by the wind as propulsive force. The optimization of route waypoints and speed in accordance with the design of Vindskip™ benefits an increase in fuel efficiency as well as a safe and comfortable voyage. The potential of the module to significantly contribute to reduced fuel costs and thus increased fuel efficiency can be concluded from the test results. The results shown in this paper demonstrate the module's ability to find the route with the lowest fuel costs based on optimum wind conditions. The displayed routes moreover indicate that the implementation of a smoothing algorithm presents potential for improvement.

Further research activities shall be dedicated to additional scenario testing. Emphasis is placed on the assessment of the influence of the weather routing module on the recommended route and according fuel savings. Thus, routes for different voyage examples and combinations of start and destination as well as weather situations shall be calculated and compared.

Thereby, the innovative ship concept of Vindskip™ can be evaluated regarding improved fuel economy and thus its potential to ensure cost efficient and sustainable sea transport.

Acknowledgment

Research providing part of the basis for this work has received funding from the European Union 7th Framework Programme under the agreement SCP2-GA-2012-314286.

References

[1] L. Walther, H.-C. Burmeister and W. Bruhn, *Safe and Efficient Autonomous Navigation with Regards to Weather*, In Bertram V. (ed.), 13th International Conference on Computer and IT-Applications in the Maritime Industries, Redworth/UK, 12-14 May 2014: pp.303-317. Hamburg: Technische Universitt Hamburg-Harburg, 2014.

[2] I. Cochran (eds.), *Voyage optimisation supersedes traditional weather routing*, In press, TANKER Operator, Vol. 14 No 4, March 2015: pp.28-29, London, England: Future Energy Publishing Ltd, 2015.

[3] V. Turau, *Algorithmische Graphentheorie*, 3rd ed., Munich, Germany: Oldenbourg Wissenschaftsverlag GmbH, 2009.

[4] C. A. Marchaj, *Aero-hydrodynamics of Sailing*, 3rd ed. London, England: Adlard Coles Nautical, 2000.

[5] IMO, *MSC/Circ. 707 Guidance to the Master for avoiding dangerous situations in following and quartering seas*, London, England: International Maritime Organisation, 1995.

[6] IMO, *MSC.1/Circ.1228 Revised guidance to the Master for avoiding dangerous situations in adverse weather and sea conditions*, London, England: International Maritime Organisation, 2007.

[7] IEC, *International Standard IEC 61174: Maritime navigation and radiocommunication equipment and systems Electronic chart display and information system (ECDIS) Operational and performance requirements, methods of testing and required test results*, 3rd ed., Geneva, Switzerland: International Electrotechnical Commission, 2008.