A route optimization method based on simulated annealing algorithm for wind-assisted ships

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Abstract. Aimed to the global demand for energy-saving and emission-reduction, and urgent need of shipping industry to cut down fuel costs, the wind-assisted ships are taken as an effective way for energy-saving and emission reduction of transoceanic crossing ships, this work focused on route optimization model to provide theoretical basis and technical support for wind-assisted ships. Firstly, this work analyses the route optimization of the wind-assisted ship, and two optimization objectives are defined. Secondly, the route optimization models for the minimum fuel consumption under the limited voyage time and the minimum voyage time on the condition of fixed main engine power were built separately, and the optimization algorithm based on simulated annealing was designed. At last, a 76,000DWT wind-assisted ship was taken as the experimental ship, and the feasibility and rationality of the model and algorithm was verified. As the simulation shown, the optimal route solved in this paper is effective in path planning problem of wind-assisted ship and has practical significance.

1. Introduction
Routing optimal for wind-assisted ships belongs to the weather routing, and the optimization of the route is the key technology of weather routing. Ship weather routing develops an optimum track for ocean voyages based on forecasts of weather, sea conditions, and a ship’s individual characteristics for a particular transit. Within specified limits of weather and sea conditions, the term optimum is used to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any desired combination of these factors [1-3].

Wind-assisted ship has a long time history which can go back to 1970s, and then from 1990s to early 2000s, the shipping industry was developing to its peak and its goal was to travel faster and faster, which lead to the very slow development of wind-assisted ships. But with the global energy-saving and emission-reduction strategies and the declining of shipping industry in the last decade, the renascence of wind-assisted ship become an effective way to solve above problems [4-5]. Current ship routing optimization study mainly focuses on the traditional ship and sailboat [6], on wind-assisted ship, there is little research available [7].

Now, with the development of the computer, the internet and communications technology has since then improved weather observation and prediction, and the highly accurate and real-time environmental data has provided a crucial basis for ship routing optimization [8]. In this paper, the
problem is modeled and abstracted into a mathematical model via an intelligent SA, and the routing optimization algorithm for wind-assisted is proposed.

2. The problem analysis

2.1. The repute optimal principle
When equipped the wind propulsion system, the power source of wind-assisted ship increased to two: main engine and Ocean wind. In this case, wind-assisted ship sails on a combination of engine and wind thrust, and its original route, such as the Great Circle route, is no longer the best one. Therefore, it is necessary to redesign the route for the wind-assisted ships to make full use of ocean wind resource as the clean energy, and improve the proportion of the power provided by the wind-assisted auxiliary propulsion system in the voyage.

The main factors affecting the navigation of wind-assisted ships are listed below:
(1) The main engine output power
(2) The type and working condition of the wind-assisted equipment
(3) The wind speed and direction
(4) The significant wave height, wave period and relative wave angle
(5) The current speed and direction.

The first two factors belong to the ship's own internal factors, and the last three ones are external influence factors. Considering the performance of wind-assisted ships including ship characteristics, wind-assisted equipment performance and by adjusting the route, the above three external influence factors: relative wind bearing, relative wave direction and relative current direction can change to fully exert the auxiliary propulsion of the ocean wind by a wind-assisted equipment. It is even possible that by adjusting the route, the navigation areas are changed to the sea where have “better” navigation conditions, thus the wind-assisted ship can also achieve the desired optimization goals.

2.2. Core problem analysis
For route optimization of wind-assisted ship, the two factors should be considered: fuel consumption and voyage time. On the condition of given speed, the ship voyage time is determined by voyage distance, while the ship fuel consumption is determined by voyage distance and the auxiliary propulsion of the ocean wind resource which is influenced by ship course, so, the optimization of the ship course and voyage distance are the keys of this work.

As we known, ship course and voyage distance are determined by waypoints of the route, thus the optimization for wind-assisted ship route is totally due to the optimal of its waypoints distribution. By adjusting the waypoints, the ship course and voyage of the route changes, and even the sea areas which the ship passes changes too, thus the ocean wind resources are also different. The change of the route and ocean wind resources in the surrounding ocean directly leads to different effects of wind resources on the ship.

2.3. Model design
The overall optimal model design for a wind-assisted ship is shown in figure 1, the route between the departure point and destination point is broken up into a waypoint sequence, after that, the waypoints are taken as variables in the subsequent route optimization process. In the optimization algorithm, a
new route is generated by adjusting the waypoints, which has different ship courses and sea area compared with the original route. At the same time, the optimization criteria and the ocean wind resources are used to evaluate the advantages or disadvantages of the new route, at last, the waypoints on the optimal route are got. From figure 1, the core problem in the route optimization of wind-assisted ship are:

1. Optimum searching model
   Including the method of adjusting the route, that is, the way to generate a new route, the principle of route reservation and abandonment, and the optimization criteria that is used to compare the new route with the original route, determine which new routes are reserved or discarded.

2. The optimization criteria
   For an optimization objective, the optimization criteria are used to assess the differences between the various routes, and compare which one is better.

3. Route optimization model of wind-assisted ship
   The main idea of wind-assisted ship route optimization is that the ship looks for “better wind” by moderate deviation if condition permits. In this condition, because of the increasing wind-assisted propulsion, the fuel consumption is reduced or voyage time is saved, although the total voyage distance is added. They are two optimization objectives, as listed follows:
   (1) Take the minimum fuel consumption as optimization objective. On the condition of fixed ship speed, the ship effectively uses the wind power assisted thrust to reduce main engine output, then makes the fuel consumption be least while maintaining the speed;
   (2) Take the minimum voyage time as optimization objective. On the condition of fixed main engine output, the ship effectively uses the wind-assisted thrust to increase speed, then shortens the sailing time of the ship and improve economic benefits.

3.1. Minimum fuel consumption model
   The optimization objective of “minimum fuel consumption” is that in the case of a ship equipped wind-assisted system, through route optimizing, the wind-assisted equipment can provide a better auxiliary thrust, thereby reduce the engine thrust, thus the fuel consumption is reduced. The work provided by main engine on the whole voyage relates to total fuel consumption, and is described as \( W_e \):

\[
W_e = \sum_{i=1}^{N-1} (T_e) \cdot S_i = \sum_{i=1}^{N-1} (R_i - (T_w)) \cdot S_i
\]

Where \( T_e \) is the engine thrust, \( R \) is the ship resistance, \( T_w \) is the wind-assisted thrust, \( N \) is the number of waypoints, \( S_i \) is the distance of rhumb line between each two succession waypoints, the total distance of the voyage is \( S = \sum_{i=1}^{N-1} S_i \).

Figure 2 is the thrust variation diagram under the condition of fixed speed of wind-assisted ship, it can be found that when sailing in this way, as the wind-assisted auxiliary thrust continues to increase, the thrust required by the engine is continuously reduced, thereby achieving the purpose of saving fuel consumption. It should be noted that when the engine thrust is reduced to a certain value, it will not be able to continue to decrease, but should be kept at a minimum value. This is because that the engine must work upon its minimum load operation to ensure the stability and reliability. So, when the wind-assisted thrust increases to a certain extent to make \( T_e < T_{e_{\text{min}}} \), in order to hold the ship speed constant, the wind-assisted system must decrease its output efficiency to reduce the auxiliary thrust, thereby maintain \( T_e = T_{e_{\text{min}}} \). In this way, the \( W_e \) is described as:
\[ W_e = \sum_{i=1}^{N-1} \max \left( \left( R_i - \left( T_{W} \right)_i \right), T_{min} \right) S_i \]  

(2)

Considering the shipping date as the constraint condition, the cost function of minimum fuel consumption optimization can be described as:

\[
\begin{aligned}
    f &= \min \left( W_e \right) \\
    t &\leq SD
\end{aligned}
\]

(3)

Where \( t \) is the total voyage time, and \( SD \) is the shipping date.

3.2. Minimum voyage time model

The optimization objective of the “minimum voyage time” is that in the case of a ship equipped wind-assisted system, through route optimizing, the wind-assisted equipment can provide better auxiliary thrust to increase ship speed, thereby reducing the voyage time, and even cutting down the fuel consumption. The total voyage time is described as:

\[
    t = \sum_{i=1}^{N-1} \frac{S_i}{v'_i} \]

(4)

Where \( v' \) is the actual ship speed which is the function of ship speed in calm wind and water, wind speed and angle from ship heading.

The wind-assisted equipment not only provides the auxiliary thrust, but also increases the ship resistance. In some time, when the auxiliary thrust is no greater than added resistance, and the speed of the ship using wind-assisted propulsion is lower than not using it, in this case, it is unnecessary to use wind-assisted system, and the wind-assisted sail just as normal ships without wind-assisted equipment. Of course, to avoid this adverse condition is what we need to do, and also the purpose of this work. However, we cannot completely avoid this situation, so, the cost function of the minimum voyage time optimization is described as:

\[
\begin{aligned}
    f &= \left\{ \begin{array}{ll}
        \min t &= \min \sum_{i=1}^{N-1} \frac{S_i}{v'_i} \\
        v' &= \max \left( v_{assisted}, v_{ship} \right)
    \end{array} \right. 
\end{aligned}
\]

(5)

Where \( v_{assisted} \) is sailing speed using wind-assisted propulsion, while \( v_{ship} \) is sailing speed without using wind-assisted propulsion.
3.3. New route generation model
As shown in figure 3, in the process of generating new route, it is not necessary to adjust all the waypoints on the previous route at the same time, but select several arbitrarily ones to change, thus generate new route and gradually optimize the route. In this way, it helps to ensure the diversity of the route and speed up the convergence of the algorithm. This is because:

(1) On one route, several waypoints may be already in the best position, and in this case, it is only necessary to adjust the local route to achieve the best. But if changing all waypoints, it is difficult to converge to the optimal.

(2) In the process of adjustment, changing of the combination of a random number of waypoints may be better than of all waypoints, so as to achieve the goal of gradual optimization of each waypoint.

For one waypoint to be adjusted, the longitude and latitude coordinates are respectively changed by generating two disturbance variables, to ensure the waypoint can be moved to any position around the initial. After obtaining the new route, it is necessary to set a strategy to determine the reservation or abandonment of the new route for different situations.

4. Simulation Results

4.1. Algorithm design
Simulated Annealing (SA) theory was firstly published by Metropolis in 1953, and applied in combination optimal problem by Kirkpatrick in 1983, Metropolis’s algorithm simulated the material as a system of particles. The algorithm simulates the cooling process by gradually lowering the temperature of the system until it converges to a steady, frozen state. The SA algorithm has the characteristics of strong global search ability and fast convergence.

Based on the SA algorithm, a route optimization intelligent algorithm is designed in this work. The random search algorithm for solving the global optimization problem generally adopts a search strategy combining a wide range of rough search and local fine search. The selection of algorithm parameters will affect the final optimization result. The optimization objective of this work requires route optimization in relatively large sea areas, which requires the initial temperature is high so that the sea areas where the optimal route point are located can be found in the earlier large-scale search stage, then the search area is gradually narrowed, finally the optimal route is got. After many experiments in this work, in order to make the optimization effect be better, the parameters of the algorithm should be set to the following values:

(1) Initial temperature \( T_0 = 200 \), it is usually set hot enough to allow a move to almost any neighbourhood states.

(2) Markov chains \( L_k = 5000 \), which is the number of iterations at each temperature.

(3) Final temperate \( T_f = 10 \), it needs to be set suitably low.

(4) Temperature decrement \( \alpha = 0.5 \), it must be set slow enough.

4.2. Ocean winds resources data
The wind field data used in this work are provided by UCAR dataset, which is monthly means grid data, its detailed coverage information is: 0.25°×0.25°, 0.125E to 359.875E and 69.875S to 69.875N (1440×560 Longitude/Latitude. The wind grid on land is set to -9999 to ensure the integrity of data structure, which can be used to locate wind data only by the using of column and row index values.

4.3. Route optimization experiment
A 76,000 DWT wind-assisted ship was taken as the experimental ship, and monthly mean wind data of June as experimental data. In the experiment, the departure point was located in 36°N, 110°E, and the
destination point was located in 10°N, 52°E, the initial route was the great circle between them. With Matlab software, the optimization algorithm is programmed and the optimal routes were calculated, the simulated results are shown in figure 4 and 5, the red dotted line is initial route, while the blue solid line is optimal route.

Figure 4. The simulation diagram of minimal fuel consumption route.

Figure 5. The simulation diagram of minimal voyage time route.

For minimal fuel consumption route in figure 4, the added voyage time is less than 100 minutes, but the work provided by wind-assisted propulsion increases by 149.56%, which leads to the cutting of work provided by main engine reaching to 11.2%, it reveals that the fuel consumption is cut by 11.2%.

For minimal voyage time route in figure 5, the voyage of the optimized route is only increased by 74 nmiles while the voyage time is reduced by 18.7 hours, meanwhile, because of the fixed main engine output, the reduction of voyage time means less fuel consumption. So, the algorithm in this work has a good optimization effect and can be used in wind-assisted ships.

5. Conclusion

For wind-assisted ships, as equipped for wind propulsion system, the ocean winds not just have speed-loss effect, but provide additional thrust. So, this work optimizes the routes so that the wind-assisted ships can fully utilize the auxiliary thrust of the ocean wind resources to achieve the goal of "minimum fuel consumption" or "minimum voyage time". As the simulation result shown, this work has a good optimization effect and can greatly improve shipping efficiency by using wind-assisted propulsion.

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