# Voyage Optimisation towards Energy Efficient Ship Operations

**T. Cui, B. Howett, R. Lu, M. Y. Kim, Y. K. Demirel, O. Turan, S. Day and A. Incecik**

Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde,

100 Montrose Street, Glasgow G4 0LZ, UK, tong.cui@strath.ac.uk

## Abstract

With the growth of shipping industry, voyage optimisation attracts attention as a way of improving energy efficiency of ship operations. It is not only related to the commercial benefit for a single shipment, but also affects ship design and shipping schedule etc. In this paper, a relatively advanced voyage optimisation model towards energy efficient shipping is introduced, which has comprehensive function modules, including grids system design and weather routing etc while taking into account the alternative energy saving devices. Through voyage optimisation, this model can provide the stakeholders a platform to develop more economical and reliable shipping route between different ports under various sea states. A case study using a bulk carrier as ship model is taken at last to prove the tool's validity.

**Keywords:** Voyage optimisation, Energy efficiency, Weather routing

## 1. Introduction

In the shipping field, energy consumption is quite huge, as almost 90% goods traded worldwide are transported by sea. With the development of marine transport and people's enhancing awareness of energy conservation, the selection of ship routes is getting more and more attention in the shipping industry. Especially in recent years, the global economic recession led to a downturn in the shipping industry, improving energy saving capability of the ship from the technical level, to minimize the cost of transportation has become a pressing issue faced by the technician. In essentially, ship route searching can be defined as an optimisation process, which is always affected by hull form, weather, sea states and ship safety, etc. To save travel time, maximise safety or energy efficiency, people have developed many kinds of optimisation methods. Most common methods are listed as below.

Calculus of variations (Bijlsma S.J, 1975) is a method that calculates the optimal heading between two points by solving Euler equation. The optimal route can be determined by refining the gradients of arbitrary objective function in a continuous optimisation process.

Isochrone method (James, 1957) is a very common method used in ship routing and even much commercial software, like OpenCPN, qtVlm etc. It generates isochrones one by one repeatedly, which means setting several lines a ship can reach after a certain time from the departure point. From these lines, a minimum ETA route can be easily determined. It also has some modified version (Hagiwara H, 1989, Hagiwara H & Spaans JA, 1987) for different calculation objectives.

The principle of Isopone method (Klompstra MB et al., 1992, Spaans JA, 1995) is similar to Isochrone method. It defines the shipping boundary with equal fuel consumption in a three-dimensional space. This method can easily obtain minimum fuel consumption route.

Dijkstra's method (Padhy, 2008; Panigrahi, 2008, Hege Eskild, 2014) was introduced to ship routing recently, which is a kind of graph searching optimisation method. Before calculation, a network was built based on grids system, and then positive weights represent passage time or fuel consumption, etc. were assigned to the graph edges. By analysing the sum of weights on this network, optimal route with different objectives can be determined.

Dynamic programming method is developed based on Bellman's principle of optimality (Bellman, 1957). The main strategy is: solving the big problem by dividing it to many sub small problems. Results from each subproblem will form the final result. Some researchers (De Wit C, 1990, Calvert S et al., 1991) developed a 2-dimensional dynamic programming (2DDP) method for ship routing problem, which takes two dimensions: latitude and longitude into account. This method simplifies the problem and reduces the calculation time.

Based on that, Wei Shao (2012) developed a 3-dimensional dynamic programming (3DDP) method, which contains 3-dimensional variables: latitude, longitude and time and uses a forward algorithm in the optimisation process. This method can provide better ship routing results without increasing much calculation cost. Besides, there are also some evolutionary algorithms, like Genetic Algorithm (Harries, 2003, Hinnenthal, 2010, and J.Szłapczy´nska, 2009).

In this paper, a voyage optimisation model towards Energy Efficient Ship Operations is introduced. This model has comprehensive function modules, including grids system design and weather routing etc while it can also take into account the alternative energy saving devices. A combination of global and local optimisation strategy is used in voyage optimisation. The model runs towards to two objectives: ETA and fuel consumption. Finally, an optimisation Pareto front can be generated, and then the optimal route according to different shipping requirements can be determined.

## 2. Voyage Optimisation Model

### 2.1. Ship performance prediction

Ship performance prediction is the basis of the whole model, which decides whether the ship operation has high quality or not. In order to obtain ship performance very quickly and conveniently, a Ship Performance Profile File, which is developed by (Howett, B., 2015), is generated from WSM (Whole Ship Model) (Low Carbon Shipping Final Report, 2014). It can be also obtained from other model, for example, when the simulation takes wind assisted technology into account, it will be obtained by WASPP (Wind Assisted Ship Performance Prediction) (Howett, B., 2015). "This file is to package performance related attributes of an individual ship for a whole range of environmental and operational conditions in a single file, allowing data to be pre-calculated for later use in time intensive applications"( Howett, B., 2015). The file format uses the netCDF (NETwork Common Data Form) specification, a selfdescribing, machine independent file format intended for string multidimensional scientific data.

One simple file contains these dimensions: speed, significant wave height, relative wave angle, true wind speed, true wind angle and an output attribute: brake power.

When the values of five dimensions are given, through the 5-D interpolation, their corresponding brake power can be obtained. So that the fuel consumption for a certain route can be calculated by:

$$FC = P_B \cdot sfoc \cdot t \tag{1}$$

Where, $FC$ is fuel consumption, $P_B$ is brake power obtained by ship performance profile, $sfoc$ (g/kWh) is specific fuel oil consumption of the engine, $t$ is ship navigation duration, which can be easily obtained when the length of the route and actual ship speed are known.

Besides, Ben also mentioned, the ship performance profile may also include additional dimensions (eg draft/loading condition) or additional attributes (eg fuel consumption) where required. So when alternative energy saving devices are taken into account, the model only needs to generate a new ship performance profile file without changing anything else. This make the voyage optimisation model combine with other technologies well.

## 2.2 Grids system design module

### 2.2.1 Main design principles

Grids system is designed in advance for leading the ship travel. In this grids system, great circle (The shortest distance between two points on a sphere) is taken as the reference, which is divided into several equal stages with certain numbers of points. Through every point, a straight line can be drawn perpendicular to its tangent line around the circle.  Next, certain numbers of points can be distributed along this vertical line, including upper and lower parts of the great circle. The number of stages and distance between two points in one stage are both adjustable. The grids system can be clearly explained in Figure 1.

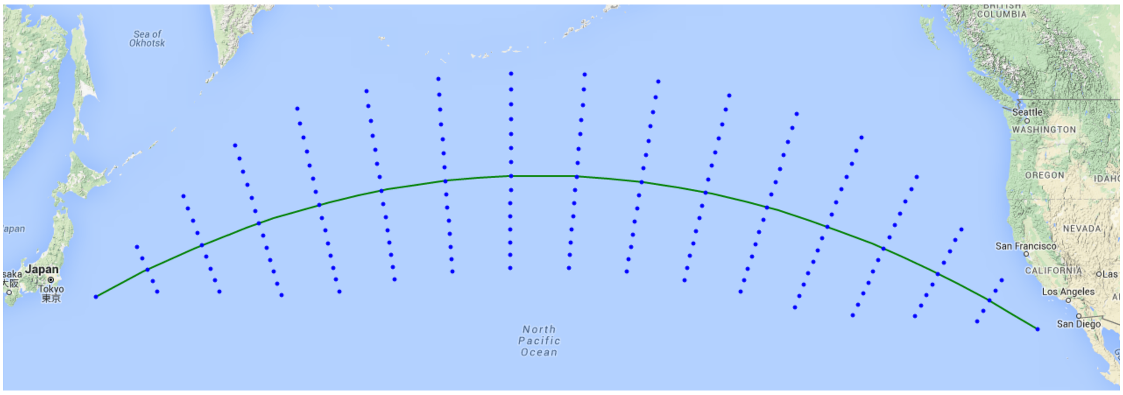


Figure 1 – Grids system

After the grids system is fixed, travel directions should be determined from every departure point to arrival point. Considering the larger course deviations are not feasible and would be unrealistic for an optimum route, five directions are better. So that, from departure point, except points near the grids border, a ship at every point can travel to next five potential points, which can be seen in Figure 2. With these nodes are connected, many potential arcs are formed.

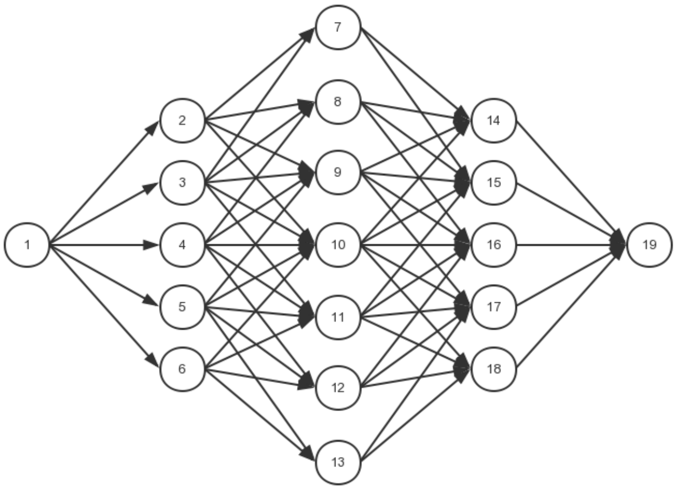


Figure 2 – Ship routing network

2.2.2 Land avoidance function

The grids system above is only suitable for open water. However, for most real situations, the ship always travels around some islands. Therefore, a land avoidance method should introduced to this module. Here, the GSHHS (A Global Self-consistent, Hierarchical, High-resolution Shorelines Geography Database) coastline data is introduced. In this data base, every island, including main land, is regarded as a polygon formed by these coastline data. So once a navigable zone is decided, several polygons can be found within this area, and then the waypoints can be operated according to two rules below:

1) If a waypoint is on this land, that means this point is in this polygon, the ship certainly will not travel through this point, so that this waypoint will be deleted.

2) If two points are both in sea, but the straight line connected these two points cross an island, in other words, there is intersection between this line and this polygon, so that this line will be deleted, that means the ship will not go along this line. It will choose next available points to sail.

Based on these basic rules, a simple land avoidance function was developed.

2.3 Weather routing module

2.3.1 Weather data

This model will take only winds, waves into account at the moment. Waves and winds data are both downloaded from ECMWF (European Centre for Medium-Range Weather Forecasts) website. The data is constructed in gridded binary (GRIB) data form, including 10 meter U wind component, 10 meter V wind component, mean wave direction, mean wave period and significant height of combined wind waves and swell, and they all update every 6 hours. All of these weather data files contain time, latitude and longitude. Once time, latitude and longitude at a certain point on the earth were given, detailed weather data at that point will be known in this module. In this research, 36 years (1979-2014) global historic weather data is downloaded for the shipping simulation.

### 2.3.2 Weather routing module

The voyage optimisation strategy used in this model is a combination of global and local optimisation with two objectives: ETA and fuel consumption.

The calculation starts from the departure point. Firstly, the model reads the weather data at the departure point by local longitude, latitude and departure time. Secondly, as can be seen from the grids system in 2.2.1 and Figure 3, the whole travel route can be divided into several stages, so that the ship can travel along the route stage by stage. Within every stage, there are many departure points and arrival points, and almost every point (without the point near the grids border) can go to next stage by five directions. So there are many potential route arcs in one stage.

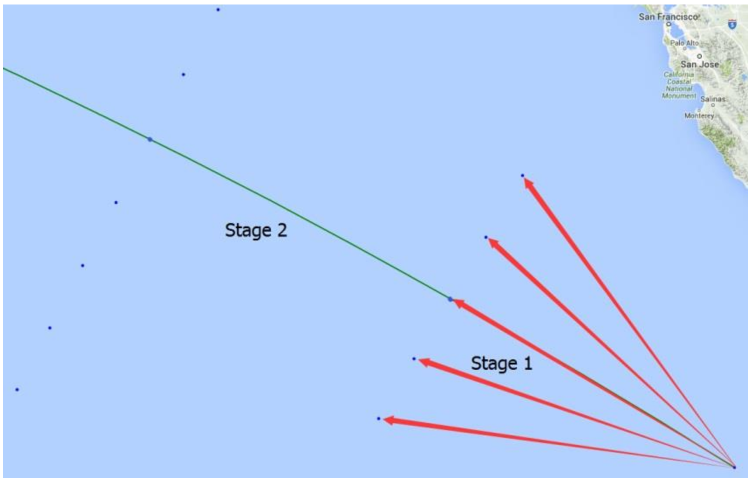


Figure 3 – Ship routing stages

In the beginning, a random speed is assigned to a travel direction in stage 1. This speed ranges from minimum speed to maximum speed with an interval speed $\Delta V$ . Having the weather data and ship speed, through 5-D interpolation in the ship performance profile file, the fuel consumption on this arc can be easily determined under these conditions. Then the navigation information of this arc under this certain condition will be stored in its arrival point, including fuel consumption, ship speed, navigation duration, local time (calculated by adding navigation duration to departure time ) and coordinates of the departure point. Next, the arrival point in Stage 1 becomes the departure point in Stage 2. According to the information stored in this point, new weather data will be read and new random speed will be assigned to a travel direction, and then new round calculation will carry out in Stage 2, and results will be accumulated to store in next arrival point.

With the same method, the fuel consumption calculation repeats over all stages until reaching the final destination point, which covers all potential route arcs, and traverses all the potential travel directions and all the speed options. After calculation, every point will store many sets of navigation results. Through continuous accumulation, each set of results presents the information of a potential route from the initial departure point to this point, which contains fuel consumption and navigation duration in every arc that the ship passed and the sum of them up to this point, and also coordinates of each point the ship passed. Finally, by checking the route information stored in final destination point, a Pareto front (ETA vs. Fuel consumption) can be drawn. And then a minimum fuel consumption route plan can be selected according to the ship navigation schedule (ETA). The whole process can be regarded as a global optimisation.

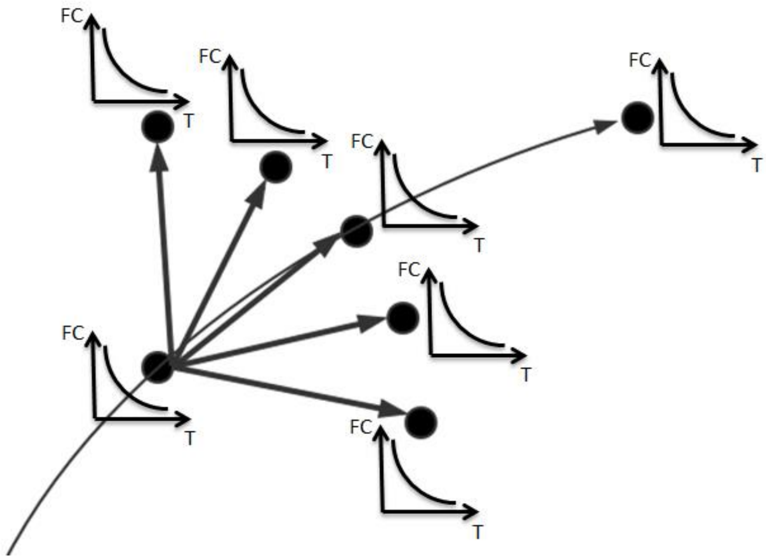


Figure 4 – Local optimisation strategy

By the way, when a ship travels from a stage to next, it will produce many different ETA and fuel consumption results due to so many speed and direction options. If continuous iteration lasts until final destination point, the quantity of final results will be prohibitively huge. This will lead to a huge calculation cost. Here, local optimisation strategy is introduced. For a certain arrival point, it is sure that it will receive many ETA and fuel consumption results from the last stage. Among them, there must be some results have same arrive time but different fuel consumption. So this method just keeps the minimum fuel consumption under every same arrival time and deletes all of the others. Thus, keeping a Pareto front for every local waypoint, as can be clearly seen in Figure 4. With this method, when fuel consumption calculation carries out from this waypoint, only the left results will be traversed. So it will definitely save the calculation cost.

## 2.4 Post processing module

This module aims to summary all navigation data for a selected route. Here, a backward iteration algorithm is introduced. As mentioned above, on one hand, during calculation, every point will store many sets of navigation results. For one certain result stored in a waypoint, it contains total duration and fuel consumption from the initial departure point to this point, duration, fuel consumption and speed at last stage that the ship passed and also coordinates of last point the ship passed. On the other hand, a Pareto front (ETA vs Fuel consumption) is also generated in final destination point at last.

Among these results in final Pareto front, if an appropriate ETA is selected, the whole corresponding route of this result will be decided. The backward iteration algorithm starts from the selected result in final destination. According to the coordinates of last waypoint stored in this selected result, the waypoint where the ship came from during last stage can be decided. In this 'last' waypoint, as mentioned in 2.3, similarly, there was also a Pareto front, what need to do next is to find which result in this Pareto front leads to the selected result in final destination. The method is that go back to the final result and find the duration and fuel consumption from initial departure point to final point and duration and fuel consumption only at last stage. Carry out the difference calculation towards to these two attributes respectively, and then the total duration and fuel consumption up to last waypoint can be obtained. Searching with the first keyword total duration and second keyword total fuel consumption on the Pareto front in the 'last' waypoint, only one matched result can be found. Therefore, this result found is the one leads to the selected result in final destination. Similarly, this result also stored same information generated from its last waypoint. Repeating this procedure to the initial waypoint, all necessary information of selected route can be obtained, including coordinates of every passed waypoint, duration, fuel consumption and speed of each stage. If necessary, this module can even provide detailed weather data at each waypoint when the ship passed by. In this model, the only input requirement is selected ETA, if that is decided, all the information of its corresponding route will show on the screen.

## 3. Case study and discussion

In this case study, a Bulk Carrier is taken as the ship model. The departure point and destination point are respectively 5°10'W \ 49°18'N and 70°31'W \ 40°48'N. Departure time is 2014-01-05, 06:00. The grids system has 14 stages, and every stage has maximum 15 vertical waypoints with equal distance of 50 nautical miles. Ship speed ranges from minimum 4 knots to 20 knots with the interval speed 0.1 knot. The ETA is set at 227 hours (average 12 knots), and interest ETA range is 6 hours (within plus or minus 3 hours).

The grids are designed as shown in Figure 5. Waypoints in red colour are detected on land by land avoidance module and will be deleted automatically.

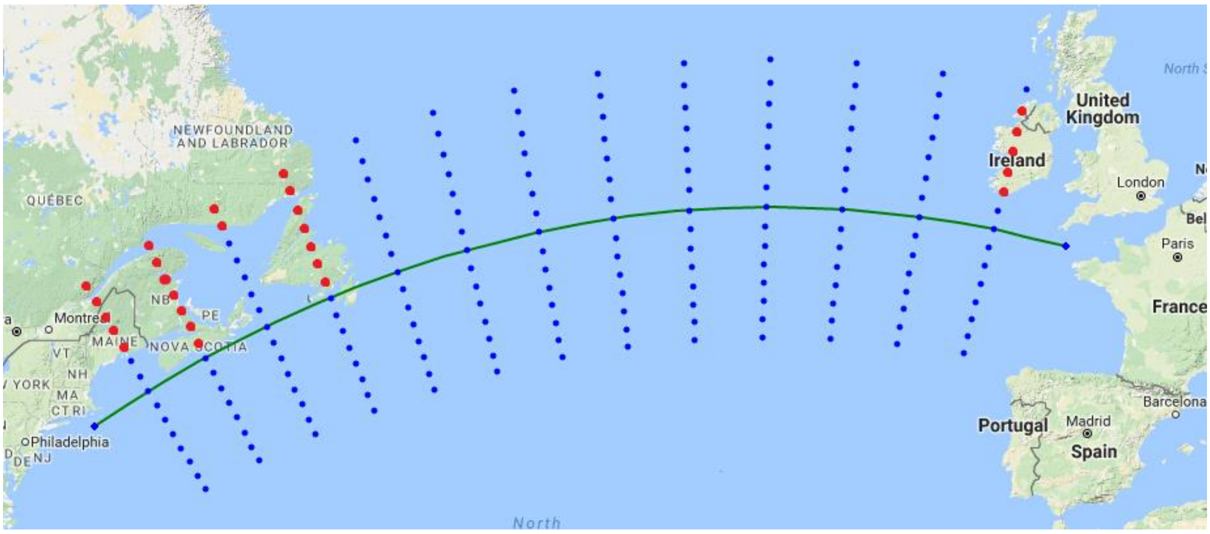


Figure 5 – Grids design of case study

The sequence of Figure 6 (a) to (c) illustrates the three days' significant wave height changing from departure time.

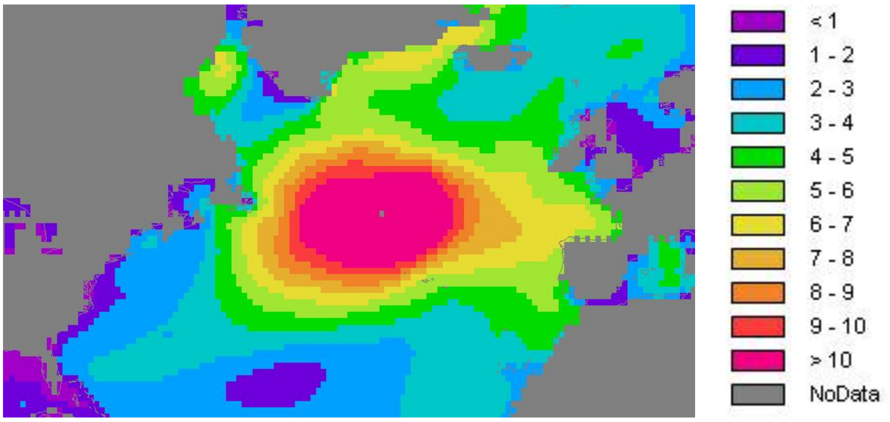


Figure 6 (a) – Significant wave height at 06:00 05/01/2014

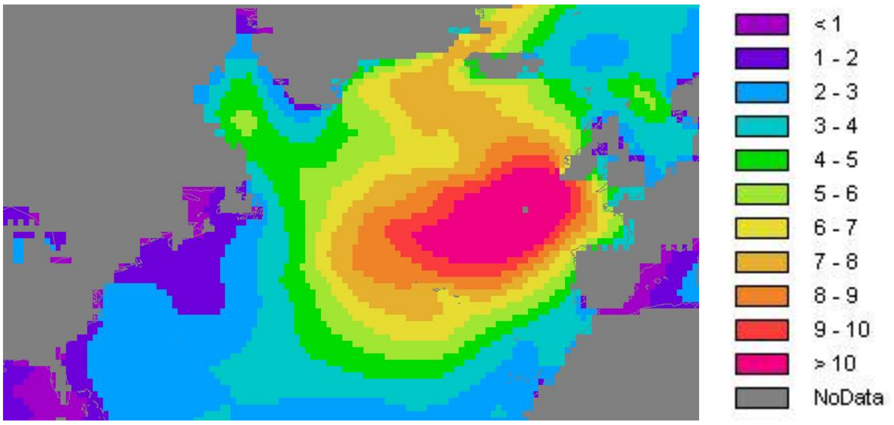


Figure 6 (b) – Significant wave height at 06:00 06/01/2014

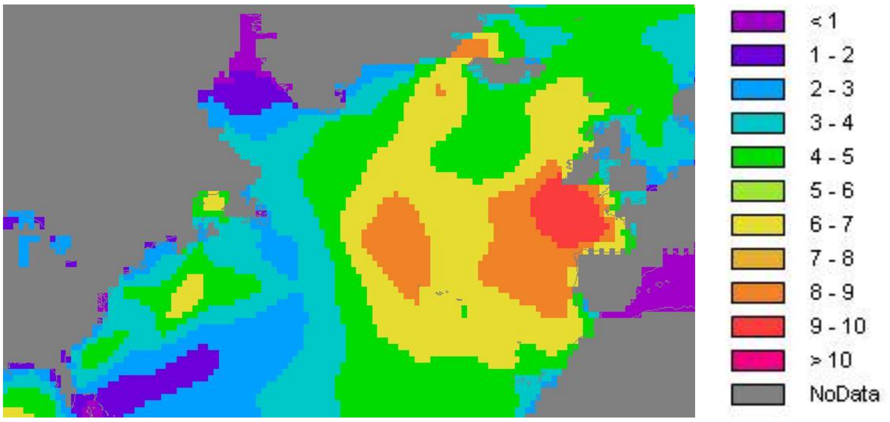


Figure 6 (c) – Significant wave height at 06:00 07/01/2014

The weather routing optimisation Pareto front results are shown in Figure 7.

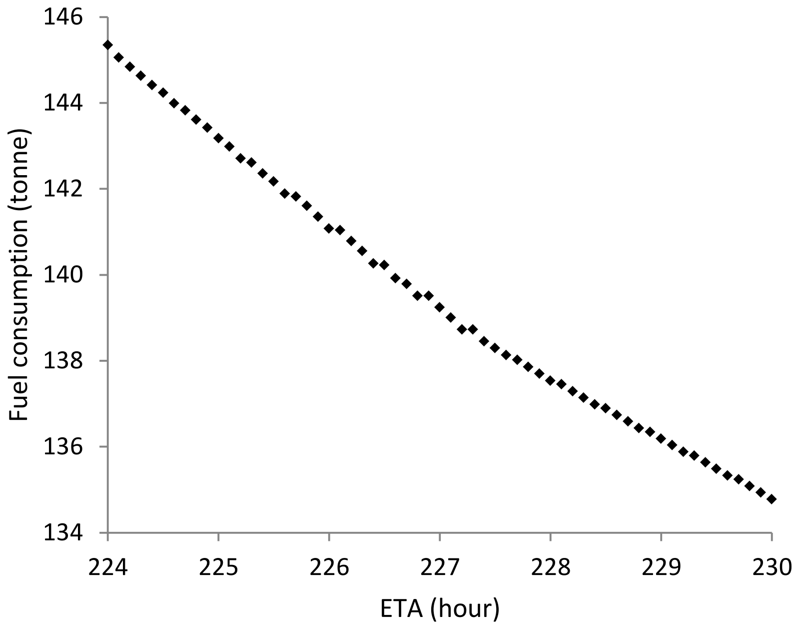


Figure 7 – Pareto front of case study

It can be seen from Fig 7. There are totally 60 potential route plans during this voyage. The ETA ranges from 224 h to 230 h, while the fuel consumption ranges from 134.78 tonnes to 145.34 tonnes. Speed sets, duration and fuel consumption distribution of three typical routes: 224 hours route, 227 hours route and 230 hours route are shown in Figure 8 (a) to (c).

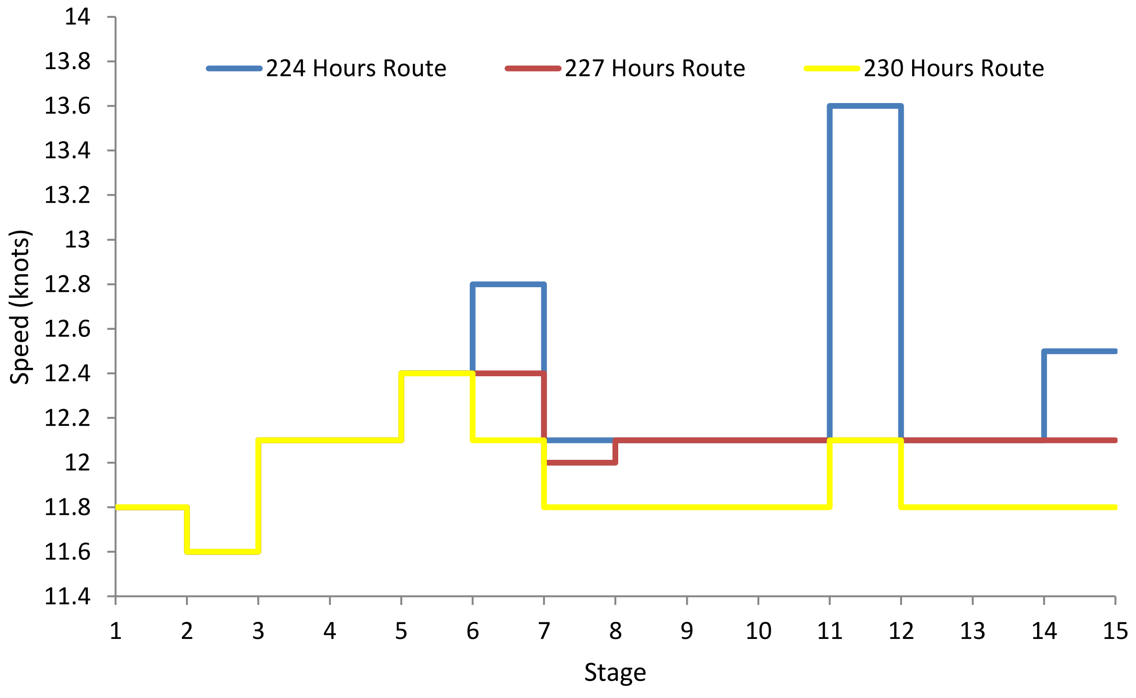


Figure 8 (a) – Ship speed at each stage

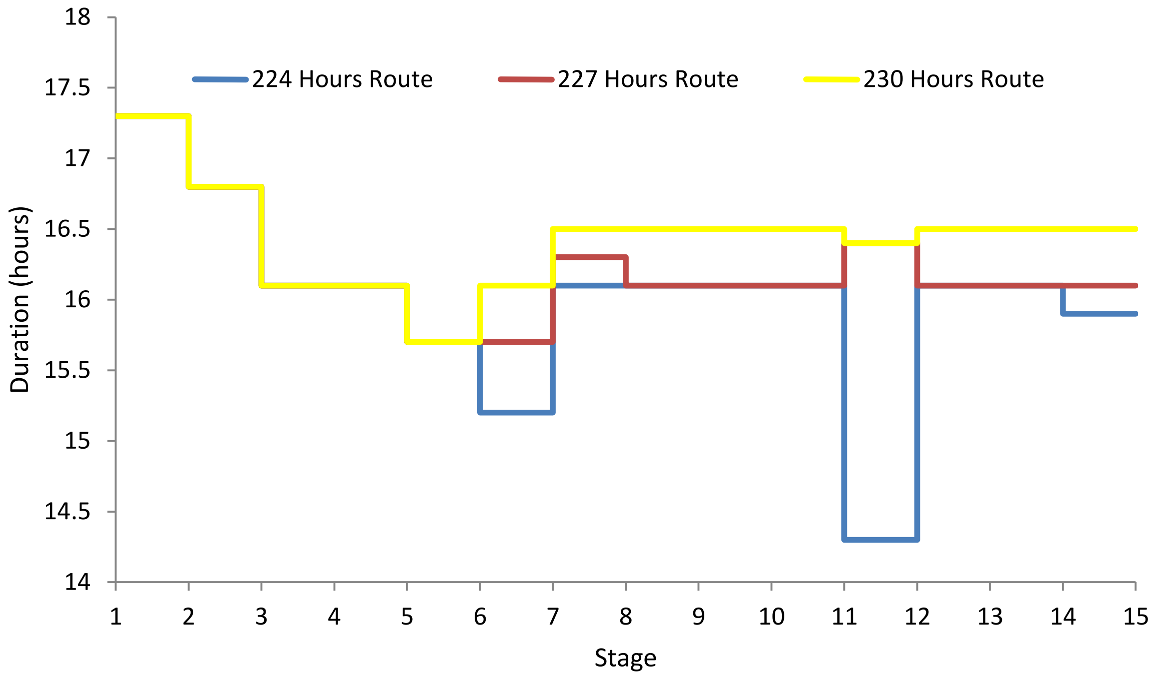


Figure 8 (b) – Duration at each stage

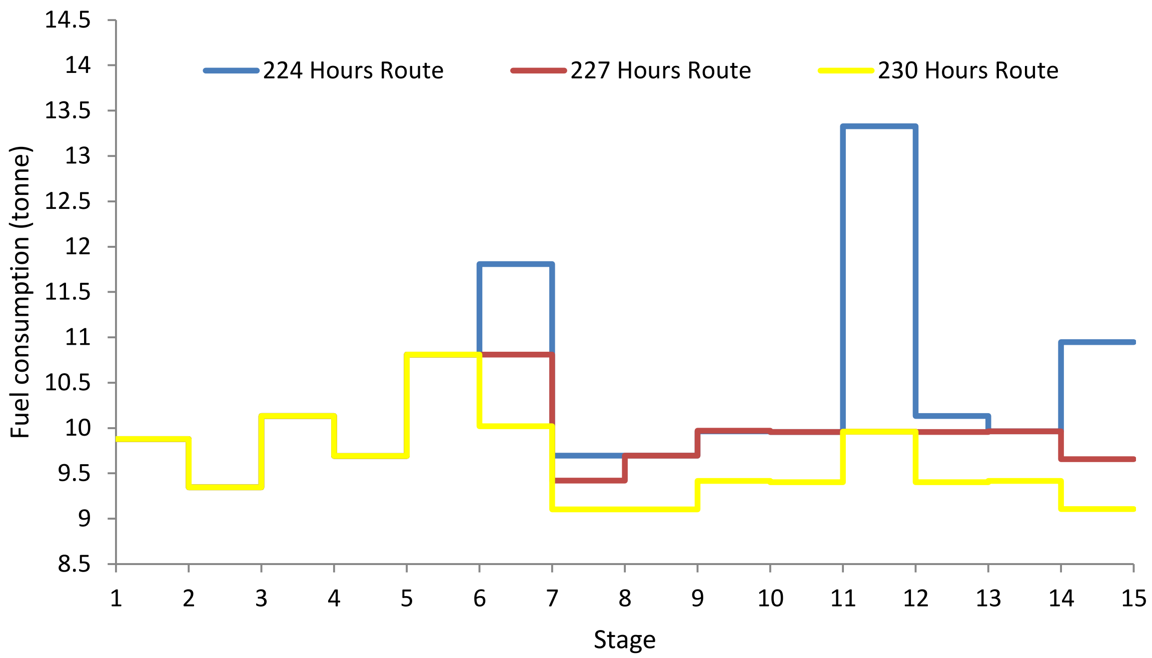


Figure 8 (c) – Fuel consumption at each stage

As can be seen from Figure 8 (a) to (c), in first 6 stages, all the trends of speed, duration and fuel consumption in the bulk carrier shipping are exactly same. From stage 7, their trends begin to behave differently. During the interested ETA range, for fastest route (224 hours), it has average 12.25 knots of speed and total 145.34 tonnes of fuel consumption; For target duration route (227 hours), it has average 12.08 knots of speed and total 139.24 tonnes of fuel consumption; While for minimum fuel consumption route (230 hours), this is certainly slowest route as well, it has average 11.91 knots of speed and total 134.78 tonnes of fuel consumption. The results show that the voyage optimisation model works very well towards energy efficient ship operations.

These three typical routes together with great circle are shown in Figure 9.


Figure 9 – Optimal routes based on different requirements

**4. Conclusion**

This paper presents a voyage optimisation model towards Energy Efficient Ship Operations. The core modules and optimisation strategy used in this model are introduced in great detail. A case study with Bulk Carrier has been made. As can be seen from results, with the strategy of a combination of global and local optimisation, this model can provide related stakeholders optimum routes towards minimum fuel consumption according to the ship navigation schedule. In the near future, more case studies will be carried out, and some key factors in this model, like grids resolution, more advanced land Avoidance method, and how to shorten calculation time etc will be studied in detail.

**Acknowledgements**

This research is part of project: Shipping in Changing Climates (EPSRC Grant no. EP/K039253/1). The author would like to express sincere thanks for the support from UK Research Council, University of Strathclyde and China Scholarship Council.

**Reference**

HOWETT,B., 2015. Report: SHIP PERFORMANCE PROFILE FILE FORMAT DEFINITION

Howett, B., Lu, R., Turan, O., Day, AH., 2015, The Use of Wind Assist Technology on Two Contrasting Route Case Studies. Shipping in Changing Climates Conference, Glasgow, Scotland, UK

BELLMAN, R.E., 1957, Dynamic Programming. (Princeton: Princeton University Press).

BIJLSMA, S.J., 1975, On Minimal-Time Ship Routing. PhD Thesis. Royal Netherlands Meteorological Institute, Delft University of Technology.

CALVERT, S., DEAKINS, E. and MOTTE, R., 1991, A Dynamic System for Fuel Optimisation Trans-Ocean. Journal of Navigation, 44 (2), 233-265.

DE WIT, C., 1990, Proposal for Low Cost Ocean Weather Routeing. Journal of Navigation, 43 (3), 428-439.

ESKILD, H., 2014, Development of a method for weather routing of ships. Master Thesis. Department of Marine Technology, Norwegian University of Science and Technology.

FALTINSEN, O. M., MINSAAS, K. J., LIAPIS, N and SKJØRDAL, S. O., 1981, Prediction of resistance and propulsion of a ship in a seaway. 13th Symposium on Naval Hydrodynamics Shipbuilding Research Association of Japan.

GERRITSMA, J., and BEUKELMAN, W., 1972, Analysis of the resistance increase in waves of a fast cargo ship. International Shipbuilding Progress, 19(217), 285–293.

HAGIWARA, H. and SPAANS, J.A., 1987, Practical Weather Routeing of Sail-Assisted Motor Vessels. Journal of Navigation, 40, 96-119.

HAGIWARA, H., 1989, Weather Routing Of (Sail-Assisted) Motor Vessels. PhD Thesis. Delft University of Technology.

HARRIES, S., HEINMANN, J. and HINNENTHAL, J., 2003, Pareto-Optimal Routing Of
Ships. International Conference on Ship and Shipping Research, Palermo.

HINNENTHAL, J., 2010, Robust Pareto-Optimum Routing of Ships Utilising Deterministic and Ensemble Weather Forecasts. PhD Thesis. Technische Universität Berlin.

HOLTROP, J., 1984, A Statistical Re-Analysis of Resistance and Propulsion Data. International Shipbuilding Progress, 31(363), 272-276.

JAMES, R.W., 1957, Application of wave forecasts to marine navigation. Washington DC: Navy Hydrographic Office.

KLOMPSTRA, M.B. et al., 1992, The Isopone Method in Optimal Control. Dynamics and Control, 2(3), 281-301.

LO, H. and McCORD, M., 1998, Adaptive ship routing through stochastic ocean currents general formulations and empirical results, Transportation Research Part A: Policy and Practice, 32(7), 547–561

LOUKAKIS, T.A., and SCLAVOUNOS, P.D., 1978. Some extensions of the classical approach to strip theory of ship motions, including the calculation of mean added forces and moments. Journal of Ship Research, 22(1), 1–19.

Low Carbon Shipping Final Report, 2014

McCORD, M. LEE Y. and LO, H., 1999, Ship routing through altimetry-derived ocean currents, Transportation Science, 33(1), 49-67

MINSAAS, K., FALTINSEN, O. M. and PERSSON, B., 1983, On the importance of added resistance, propeller immersion and propeller ventilation for large ships in a seaway. 2nd International Symposium on Practical Design in Shipbuilding (PRADS`83), Tokyo & Seoul, October, 149-159.

NORDFORSK, 1987. Assessment of a ship performance in a seaway.

PADHY, C.P, SEN, D. and BHASKARAN, P.K. 2008, Application of wave model for weather routing of ships in the North Indian Ocean'. Natural Hazards, 44(3), 373–385.

PANIGRAHI, J.K. and UMESH, P.A., 2008, Minimal Time Ship Routing Using IRSP4 (MSMR) Analyzed Wind Fields. Marine Geodesy, 31(1), 39–48.

SHAO, W., ZHOU, P., THONG, S. K., 2012, Development of a novel forward dynamic
programming method for weather routing. Journal of Marine Science and Technology
17(2), 239–251.

SPAANS, J.A., 1995, New Developments in Ship Weather Routing. Navigation, 169, 95-106.

SZLAPCZY´NSKA, J. and SMIERZCHALSKI, R., 2007, Adopted Isochrones Method Improving Ship Safety in Weather Routing With Evolutionary Approach. International Journal of Reliability, Quality and Safety Engineering, 14(6), 635-645.