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Development of a Ship Weather Routing System towards Energy Efficient Shipping

By

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Declaration

This thesis is the result of the author's original research. It has been completed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Date:

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Nomenclature

AIS	Automatic Identification System
COT	Crude Oil Tanker
DWT	Dead Weight Tonnage
ECMWF	European Centre for Medium-Range Weather Forecasts
EEO	Energy Efficiency of Operation
ETA	Estimated Time Arrival
FC	Fuel Consumption
FCR	Fuel Consumption Rate
GCR	Great Circle Route
GHG	Greenhouse Gas
GRIB	GRIdded Binary or General Regularly-distributed Information in Binary Form
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography Database
ICS	International Chamber of Shipping
IMO	International Maritime Organisation
LCS	Low Carbon Shipping
netCDF	NETwork Common Data Form
NOAA	National Oceanic and Atmospheric Administration

RAO	Response Amplitude Operator
RCUK	Research Councils UK
RMS	Root Mean Square
RPM	Revolutions Per Minute
SCC	Shipping in Changing Climates
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption of the Engine
SPP	Ship Performance Profile File

Abstract

The energy consumption and the Greenhouse Gas (GHG) emissions from shipping field are vast and very important which cannot be ignored for both economic and environmental reasons. Improving energy efficiency of the ship through the technical and operational means has become a pressing issue faced by the shipping industry. In this context, ship weather routing technique, as one of the effective energy efficiency improvement methods has attracted more and more interests from technical staff.

A ship weather routing system towards energy efficiency is developed in this study. This system consists of six modules which are ship performance calculation module, grids system design module, weather data module, ship safety module, weather routing module and post-processing module. These modules basically cover the essential elements of a ship weather routing system.

Among them, the calculation methods of various ship performances are utilised in ship performance module; The design principle of grids system and an intelligent land avoidance function are developed in grids system design module; The acquisition and decoding of weather data files are introduced in weather data module; A ship safety guidance is selected and followed in ship safety module; A combination of global and local optimization algorithm is adopted in weather routing module; A backward iteration algorithm is developed and the visualization of result routes is implemented in the post-processing module. The role of each module and the data transfer relationship between these modules are described in detail.

Next, seven effective methods are introduced to upgrade the system. These methods which can greatly improve the working efficiency of the system are respectively: create ship performance database, redefine ship travel principle and adjust the grids system scale, merge ship safety module to ship performance prediction module, delete results in every waypoint which cannot meet the time schedule, set the speed control parameter, delete results in every waypoint which cannot meet expected fuel consumption and optimise programming codes. With these methods introduced, the structure and operation logic of the system also becomes more effective.

A series of representative case studies are carried out to verify the proposed methodology and the tool. Finally, the approach is implemented on a container ship in both purely motorised and Flettner rotor assisted propulsion conditions, to see the energy efficiency gained through Flettner rotor technology. Case studies in various shipping routes, departure times and ship speeds are carried out based on this system and finally a framework for assessing the performance of wind assist technology is proposed.

The proposed weather routing system has significant practical application and can provide an effective reference for related research in the shipping industry.

1 Introduction

1.1 Background

Global shipping plays a great role in the continuing and sustainable development of the world economy, as almost 90% of trade in goods, energy and raw materials worldwide are transported by sea. International Chamber of Shipping (ICS, 2014, 2017) predicted that the seaborne trade would increase from 10 billion tonnes to 17 billion tonnes by the year 2030 to meet the growth of world's population and economy, as can be seen in Figure 1.1.

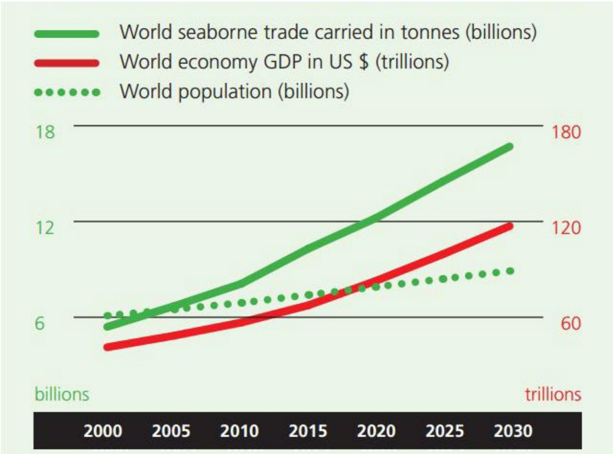


Figure 1.1 Predicted increases in world seaborne trade, GDP and population (ICS, 2014)

The fuel consumption (FC) and the Greenhouse Gas (GHG) emissions from shipping field are major topics of interest. The International Maritime Organisation (IMO) estimates that from 2007 to 2012, the world's marine fleet consumed between 250 and 325 million tonnes of fuel annually and that increased to 350 million tonnes annually these years (International Renewable Energy Agency, 2015). BP Marine Fuels (2016) even predicted that if economic growth improves, global demand for marine bunker fuels could grow by as much as 25% in 2018. Because with a healthier economy the need to move cargoes fast will require vessels to speed up and bunker consumption will increase. Currently, marine fuel constitutes 6.1% of global world oil demand while residual marine Fuel accounts for 49.5% of total global residual demand (Concawe, 2016). On the other hand, international shipping accounts for approximately 2.8% of annual global greenhouse gas emissions (3.1% of CO2 annual emissions). Just for the year 2012, total shipping emissions were approximately 938 million tonnes CO_2 and 961 million tonnes CO_2e for GHGs combining CO_2, CH_4 and N_2O (IMO, 2014). Compared to other modes of transport, although shipping produces the lowest emissions of carbon dioxide (CO_2) per tonne per kilometer travelled, emissions are still expected to rise with shipping demand and could triple by 2050 if left uncontrolled (International Renewable Energy Agency, 2015).

Since energy saving and emission reduction have become very important factors that cannot be ignored for both environmental and economic benefits, the modern shipping industry is paying more and more attention to them.

1.2 Problem definition and motivation

In recent years, as the main regulatory body for shipping, the International Maritime Organisation (IMO) has raised several technical and operational measures towards regulating shipping energy efficiency and thereby controlling the marine GHG emissions. One of the most important concepts is SEEMP, which is Ship Energy Efficiency Management Plan.

The SEEMP is a management tool to assist ship owners in managing the energy efficiency of their ships (Lloyd's Register, 2012). It is applicable on a mandatory basis from 2013 and is designed to provide possible approaches for improving ship and fleet efficiency performance over time and some options to be considered for optimising the performance of the ship. The IMO introduced the SEEMP as a mandatory tool under MARPOL Annex VI (MARPOL: International Convention for the Prevention of Pollution from Ships, Annex VI: Prevention of air pollution from ships), entering into force on January 1, 2013.

There are many categories of energy efficiency improvement methods for potential adoption within each ship's SEEMP, including Fuel-efficient ship operations, Optimised Ship Handling, Hull Maintenance, Propulsion System, or even Waste Heat Recovery. For the category of Fuel-efficient ship operations recommended by SEEMP (IMO, 2016), it includes:

- Improved voyage planning

- Weather routing

- Just in time delivery

- Speed optimisation

- Optimised shaft power

Among them, speed optimisation and weather routing are two very common and effective tools for energy efficient ship operations (IMO, 2012, 2016; Simonsen, et al, 2015).

According to IMO, both weather routing and speed optimisation have a high potential for efficiency savings on specific routes and they are commercially available for all types of ship and for many trade areas, although these services have some disadvantages, such as they are always expensive and their all require complex data collection processes and so on.

Speed optimisation means to select an optimum speed changing strategy for a given route towards some specific objectives like fuel consumption or arrival time. For example, if the objective is minimum fuel consumption, optimum speed means the speed at which the fuel used per tonne mile is at a minimum level for that voyage. It does not mean minimum speed, in fact, sailing at less than optimum speed may consume more fuel rather than less under some special conditions. Reference should be made to the engine manufacturer's power/consumption curve and the ship's propeller curve (IMO, 2016).

Ship weather routing is used to determine the optimum voyage plan (course and speed) between given departure and destination ports based on weather conditions and ship’s corresponding performance. It always aims to minimise fuel consumption, suitable estimated time arrival (ETA) or maximum ship safety and other goals. Traditional weather routing did not consider speed optimisation. It only served its purpose of avoiding bad weather in the past, which could not meet the requirement that shipping companies attempt to minimise fuel consumption. Modern weather routing not only takes speed optimisation into account but also considers ship response, engine performance and accurate data sources and so on. In this research, weather routing adopts the latter concept, and a voyage optimisation strategy will also be developed, which can also be applicable to fleets.

Ship weather routing services provide benefits primarily for increased safety, time saving, cost reductions and environmental enhancement. An effective weather routing service can maximise shipping safety by avoiding heavy weather, which can significantly reduce the probability of severe damage to the ship and injury of crew members. The savings in operating costs are derived from reductions in transit time, heavy weather encounters, fuel consumption, cargo and hull damage, and more efficient scheduling of dockside activities. Besides, with better voyage operating plans and high energy efficiency measures, weather routing can also achieve the environmental enhancement by reducing air emissions (including CO_2, NO_x and SO_x) (American Practical Navigator, 2002).

Although many agencies are offering weather routing services to the shipping industry, most of the commercial ship navigation is still based on operators' experience and knowledge. In order to cooperate with IMO strategy towards regulating shipping energy efficiency and thereby controlling the marine GHG emissions, the shipping industry are seeking to be upgraded. Academia also takes an active part in this revolution trying to help industry understand the scope for greater energy efficiency of the supply side, the demand side drivers and the supply and demand interactions in shipping (Shipping in Changing Climates project, 2013).

For this purpose, The Research Councils UK (RCUK) put forward a proposal for low-carbon shipping in 2009. The project of "Low Carbon Shipping - A Systems Approach" (LCS) jointly submitted by University College London, Newcastle University, University of Strathclyde, University of Hull and University of Plymouth has been approved, and has also received support from many partners in the industry, including Shell, Lloyd's Register, BMT and Rolls-Royce (Low Carbon Shipping Project, 2010, 2014).

According to its official introduction, the project aims were:

1. To develop knowledge and understanding of the shipping system, particularly the relationship between its principal components, transport logistics and ship designs, and clarify the many complex interfaces in the shipping industry (port operations, *owner/operator relationships, contractual agreements and the links to other transport modes).*

2. To deploy that understanding to explore future logistical and ship concepts and how they could achieve cost-effective reduction of carbon emissions.

3. To develop projections for future trends in the demand for shipping, the impacts of technical and policy solutions and their associated implementation barriers, and the most just measurement and apportionment mechanisms.

With unremitting efforts by a multidisciplinary team (geographers, economists, naval architects, marine engineers, human factors experts, and energy modelers), the project successfully concluded in June 2013 and achieved expected results.

Based on the success of LCS project, its continuing project, Shipping in Changing Climates (SCC) project, was also approved (Shipping in Changing Climates project, 2013). The project partners added the University of Southampton, University of Manchester and MSI company.

The overall aims of the SCC project are to achieve the following:

Connect, for the first time, the latest climate change impact and adaptation analysis with knowledge and models of the shipping industry to explore its vulnerability to changing climates.

Develop greater understanding of the role of shipping in underpinning future food and fuel security in a carbon and climate constrained world.

Consolidate research taking place across a number of research projects (engineering, energy systems and shipping), both in the UK and elsewhere

Further develop the modelling capacity developed under RCUK Energy's 2009 Low Carbon Shipping project to answer the increasing number of new questions that are emerging both since 2009 and as a result of research carried out in the last 3 years.

Achieve, through improved data and modelling techniques, an unprecedented level of credibility for models and analysis of the shipping system to enable shipping industry stakeholders and policy makers to manage uncertainty, and take the long term view.

Integrate knowledge about public and private law to identify policy options at all levels of governance and the options for private standard setting bodies (such as classification societies) to achieve significant GHG savings in a manner which is consistent with other concerns.

Engage in the UK and EU debate around control of its shipping GHG emissions, and to provide the tools to assess how governments and stakeholders can most effectively influence the pathway of a global industry, while taking into account legal and other constraints.

It can be seen that the new project puts higher requirements on both the depth and breadth of the research. In this project, as an important participant, one of the main tasks of the University of Strathclyde was to develop a tool to simulate the ship's shipping process. This tool is mainly for energy-saving purposes. It needs to comprehensively consider the external environment and various factors related to the internal system of the ship and can evaluate the effectiveness of the ship's energy saving and emission reduction technologies.

The study of this thesis is part of the SCC project. In this study, a new weather routing system is needed to be developed to help industry and academia understand the intrinsic mechanism at a very deep level on the subject of weather condition, ship system, ship response, energy efficiency and so on.

1.3 Objectives

The main aim of this thesis is to develop an intelligent ship weather routing system to support energy efficient shipping, which can fully reflect the impact of weather conditions on the shipping and achieve the ship's automatic voyage optimisation. The system must have complete basic functions and necessary modules including ship performance calculation module, ship navigation safety module, grids system design module, weather data processing module, weather routing module and post-processing module must be available. A well-established system must have practical application value, and can provide a reliable shipping strategy for users in the industry and academia very efficiently, and help them achieve the goal of energy conservation and emission reduction through appropriate ship routing operations. The system should be cost effective, which means that the system must not only be easy to operate but also include as much known historical data as possible, rather than cost more to collect and process other data. This also allows the user to operate the system within the office and to develop a navigation plan for the ship before it leaves. In addition, the system can also implement real-time voyage plan updates and fit well with newly introduced energy-saving technologies. Once new conditions are entered, the system can provide users with new navigation plans in a timely manner.

Based on the main aim, the specific objectives are proposed as follows:

- To review the research status of voyage optimisation strategies and applied weather routing algorithms in detail, compare the existed weather routing services in the market and identify their limitation.
- To design the structure of the weather routing system, identify the required function modules and data and algorithms that need to be integrated into each module, aimed at the limitation summarised above.
- To develop an automatic grids system design principle including an intelligent land avoidance function that makes the system applicable to most of the world's navigational areas.
- To develop a weather routing algorithm to achieve global and local optimisation of voyage plan, including the automatic speed optimisation.
- To develop an interface for the system so that the system can be easily combined with the newly introduced technology.
- To validate the proposed system based on several representative case studies.
- To study the impact of Flettner rotor technology on fuel consumption of the ship as a demonstration study based on the proposed system.

1.4 Main contributions and novelties

Finally, this research successfully makes some contributions to address these objectives. The main contributions and novelties of this research include:

1. The system achieves automatic speed optimisation. The system can calculate all the speed options automatically within the allowable range, and then determine the speed operation plan through optimisation.

2. The system integrates various empirical and numerical computation methods for multiple ship performances calculation, which can fully reflect the weather's impact on shipping. The system can provide reasonable ship operations with various weather conditions.

3. By integrating the 36-year history weather database, the system can make voyage plans based on past weather data before the ship departure. Because the weather in the ocean changes little every year, the voyage plan predicted based on past weather data can serve as a good reference. Even if the ship receives new weather forecast data during the journey, the system can adjust the voyage plan in time.

4. An Intelligent method to design the grids system is developed, including intelligent land avoidance function, which makes the designed grids system can meet almost all shipping routes in the world. The system can automatically generate the suitable grids system only by entering the position of the departure point and destination point, as well as the required waypoints resolution.

5. A combination of global and local optimisation algorithm is developed as the weather routing strategy of the system. This algorithm improves the system's computational efficiency while achieving automatic optimisation of speed and direction. The system can not only obtain the global optimal solution, but also obtain the local optimal solution for each path point.

6. The proposed approach and the developed tool provide the optimum energy efficient route while taking into account safety to make sure that energy efficient routes do not create unsafe conditions.

7. A series of methods are designed to improve the system's working efficiency and make the system more versatile. The system can be easily combined with various shipping energy-saving technologies. So when new technology is introduced, the system can carry out the corresponding weather routing optimisation based on user’s requirements and assess the benefit of the new technology towards energy efficiency.

8. Based on the proposed weather routing system, the impact of wind assist technology 'Flettner Rotors' on fuel consumption of ship is studied as a case study. A framework for assessing the performance of wind assist technology is proposed.

1.5 Structure of the thesis

This thesis consists of nine chapters:

Chapter 1 presents the background, the current problems definition and the motivations of the research, and lists the main objectives and contributions of the study, as well as the structure of the thesis.

Chapter 2 details the developments in voyage optimisation, summarises currently applied algorithms for weather routing, and reviews current relatively popular ship routing services. Besides, several wind assist technologies in shipping field are also reviewed. The limitations of these researches are sorted out.

Chapter 3 briefly introduces the structure of the weather routing system which contains six modules: ship performance calculation module, grids system design module, weather data module, ship safety module, weather routing module and post-processing module and introduces the methodology of the proposed weather routing system from the perspective of each module.

Chapter 4 introduces the necessary knowledge before developing the ship weather routing system. These knowledge contains two parts. The first part is the calculation principles of various ship performances including ship calm water resistance, added resistance due to waves and winds, ship propulsion and ship safety performance. The second part is the introduction of the environmental conditions including the weather data and geographical data that will be used in the system.

Chapter 5 formally introduces the proposed system. The role of each module and the relationship between them are introduced in detail. The algorithm and data needs to be integrated in each module are described in detail. A case study of a 115K DWT Crude Oil Tanker sailing along the real routes is carried out to verify the feasibility of the system preliminarily.

Chapter 6 introduces seven methods to improve the working efficiency of the system. The introduction of these methods also makes the structure and logic of the system more reasonable. A case study of a 35,500DWT Bulk Carrier sailing in the North Atlantic Ocean proves that these methods can greatly save computational costs without affecting the optimal results.

Chapter 7 formally tests and verifies the system through two representative case studies still based on the 35,500DWT Bulk Carrier but in different sailing conditions.

Chapter 8 studies the impact of the Flettner rotor as a wind assist technology on the energy efficiency of ships based on the proposed system. Several case studies for the KCS container ship with pure motorised and Flettner rotors modes are carried out for comparison purposes. Various sailing conditions including different sailing speeds, different sailing areas, different sailing directions and different sailing seasons are considered. A series of important conclusions are extracted and a framework for assessing the performance of wind assist technology is proposed.

Chapter 9 gives the discussion and conclusion of the thesis and re-emphasises the main contribution and novelties of the study, and proposes some suggestions for further research as well.

It is noteworthy that, in this study, if there's no special instruction, all the waypoints and potential routes are plotted on the digital world map, which have been generated using the route display tool mentioned in Section 5.2.7.

2 Critical Review

2.1 Introduction

This chapter aims to provide a comprehensive and in-depth review of relevant knowledge in ship routing field. Firstly, Section 2.2 summaries the current research situation of voyage optimisation, especially speed optimisation. Next, the applied algorithms for weather routing are reviewed in detail in Section 2.3 as the emphasis of this research is on weather routing technology. After that, various popular ship routing services are reviewed in Section 2.4. Finally, various wind assist technologies are described in Section 2.5. All of the above will contribute to a better understanding of the contents of this thesis.

2.2 Voyage optimisation

Voyage optimisation, as an effective shipping technology, plays a crucial role in marine transportation and attracts more and more interests from the shipping industry due to increasing economic and environmental demand. Generally speaking, voyage optimisation technology optimises ship speed and course simultaneously while taking into consideration various constraints and objectives.

According to Ottaviani (2016), voyage optimisation should be carried out based on accurate predictions of ship response in calm weather, added resistance due to sea states especially severe weather, engine and propulsion system performance and limits and so on. It should meet the requirements of strong coupling between simulation and optimisation and fast computation to manage a huge number of alternatives. The simulation outputs should be propeller speed and pitch, engine power, fuel consumption, exhaust emissions and other parameters. The objective functions of voyage optimisation are various such as minimum fuel consumption along the voyage, voyage time, maximum allowed delay, comfort indexes, number of course/speed changes and the even possible trade-off between objective functions and constraints. There are also various constraints that voyage optimisation must not break such as constrained waypoints, geometry shoreline, maximum wave height, maximum wind speed, encounter angles, wave loads and even ship motions. Constraints may be strict or feasible which depends on the rigour of operator's requirements for voyage optimisation. Both the objectives and constraints of voyage optimisation can be determined according to the emphasis of the different shipping tasks.

Voyage optimisation contributes to reducing fuel consumption and Greenhouse Gas emissions and increasing energy efficiency and shipping safety. In addition to the economic and environmental aspects, the benefits of voyage optimisation can be further extended to ship design, fleet deployment, and operational logistics (Chen, 2013). The technology can provide a reference for ship design criteria determination such as speed, sea margin, maximum ship motions and even bending moment by repeatedly simulating voyages using historical weather databases and automatic identification system (AIS) data. It helps to optimise the deployment and schedule of vessels to improve the schedule reliability for commercial shipping. It also helps to provide a more efficient schedule in terms of on-shore operations such as loading and unloading of trucks and trains by estimating the on-time arrival probability of every shipping task. Moreover, voyage optimisation can also extend the fatigue life of ship structures by predicting stress cycles and providing ship operators with seakeeping and manoeuvrability guidance for reducing ship stresses.

If taking one further step, it becomes evident that utilising a good tool for speed optimisation is the core of voyage optimisation. At the operational level, a ship which goes slower will always generate much less operating costs and emissions than the same ship goes faster, due to the non-linear relationship between speed and fuel consumption. So if the ship purposely reduces its speed to a certain extent, it can gain much economic and environmental benefit. This practice of reducing speed is known as “slow steaming” and is being applied in almost every commercial ship sector these days (Psaraftis, et al, 2014). However, this only makes sense in most normal circumstances. When shipping in severe head sea and wind conditions, the ship will use much more horsepower than that required for calm sea in order to maintain speed. This gives birth to another strategy that the ship could slow down in severe head seas and speed up in beam/following seas to catch up. Without breaking the planned shipping schedule, this strategy not only increases the energy efficiency but also prevents the ship from being damaged in severe weather. Since a shipping task is a complex systematic project, speed optimisation should be carried out based on a comprehensive consideration of the impacts of fuel consumption, gas emissions, weather conditions, on-time arrival and other conditions. However, this requires a powerful weather routing tool to determine the most optimum speed and direction for each leg of the sailing.

Many scholars have contributed to the research on ship voyage optimisation. Ronen and Christiansen, et al (1983, 1993, 2004 and 2012) made a great contribution to the overview of ship routing, scheduling, and other related problems. Their papers cover almost 40 years of development in these fields and have become the most comprehensive and valuable references. Psaraftis and Kontovas (2013, 2014 and 2016) also keep following the most advanced research in speed optimisation fields. They make a comprehensive review of speed models in maritime transportation and classify the speed models by whether or not considering emissions. What is more, Meng and Wang, et al (2010, 2011, 2012 and 2014) also actively engaged in the overview of routing and scheduling problems in liner shipping. They mainly focused on the development of speed optimisation methods, schedule design strategies, fleet deployment plans, especially for container ships. They utilised a mixed-integer nonlinear stochastic programming model, a branch-and-bound based e-optimal algorithm, average approximation method, linearisation techniques and even a decomposition scheme in their research.

Together with Meng, Gelareh (Gelareh and Meng, 2010) also proposed a mixed-integer linear programming formulation for a short-term fleet deployment problem of liner shipping operations, which is equivalently transformed from the nonlinear mixed-integer programming model by means of a linearisation technique.

Notteboom, et al (2009) looked at speed optimisation and discussed the impact of high fuel costs on the design of liner services on a single ship route. In order to deal with the impact of increasing bunker costs, they developed a cost model to assess how shipping lines have adapted their liner service schedules.

Lang, et al (2010) assumed a linearised speed model on the arrival planning strategies research. This model simplifies the nonlinear function between the fuel consumption rate and the sailing speed by linear regression. Based on that, Du, et al (2011) developed a more accurate speed model in which a non-linear and not necessarily cubic fuel consumption function is obtained by regression analysis. They used it for a berth allocation problem. After that, Wang, et al (2013) upgraded this model with a two quadratic outer approximation approaches that can handle general fuel consumption rate functions more efficiently for berthing problem. Besides, Alvarez, et al (2010) presented a discrete event simulation model, with an embedded mixed-integer optimisation routine, as the appropriate framework to assess vessel berthing and speed optimisation policies.

Norstad, et al (2011) introduced and solved a tramp ship routing and scheduling problem with speed optimisation (TSRSPSO) in which speed is a decision variable on the different sailing legs. They presented two algorithms: Discretizing arrival times and the recursive smoothing algorithm for the speed optimisation problem along a single shipping route and described a multi-start local search heuristic for the TSRSPSO. Golias, et al. (2010) also optimised the speed of containerships arriving at a port by a genetic algorithm-based heuristic, from the viewpoint of the joint planning of shipping and port operations.

Ronen (2011) constructed a cost model to analyse the relationship among oil price, sailing speed, service frequency and the number of vessels operating on a container line route with the purpose of minimising the annual operating cost of the route.

Yao, et al. (2012) summarised an empirical model that contains bunker fuel consumption rate and ship speed based on ships of similar sizes from only one shipping liner company. They highlighted that the bunker fuel consumption rate can be very different for different ship sizes and this may have a significant effect on the optimal bunker fuel management decisions.

Kim, et al (2014, 2016) considered the multiple time windows for each port call as a constraint in the ship speed optimisation problem. They formulate the problem as a nonlinearly mixed integer program and develop an optimal algorithm based on the intrinsic properties of the problem.

Wang, et al (2015) developed a sailing speed optimisation models considering ship carbon emission, demurrage and dispatch in voyage chartering ship. Two different forms of carbon emission taxation are emphatically analysed. They concluded that taxing emission based on carbon emission could lead to less profit reduction and more carbon emission reduction than taxing emissions that exceed a certain threshold.

Lindstad, et al (2015) also demonstrates slower speed is one of three answers that reduce energy consumption and GHG emissions in maritime transport (The other two are larger vessels and slender hull designs). They have a novel finding that the rise of bunker costs as a result of emission costs may cause more speed and emissions reduction than that result from higher oil prices. Because higher oil prices could raise capital tied up in cargo, so that driven by interests, cargo owners may accept the operation of speeding up which could partly counteract the trend of slowing down the vessel caused by fuel costs increase. In contrast, emission costs could not raise cargo values.

More recently, Aydin, et al (2017) also addressed the speed optimisation problem in liner shipping by considering stochastic port times and time windows. The objective is to minimise the total fuel consumption while maintaining the schedule reliability. They developed a dynamic programming model by discretising the port arrival times to provide approximate solutions and also proposed a dynamic programming model to plan the bunkering operation.

Gusti, et al (2017) presented a speed optimisation model based on information of sailing speed, displacement, sailing time and specific fuel consumption obtained from shipping log data.

Fukasawa, et al (2017) put forward a joint routing and speed optimisation model to minimise the total shipping cost and propose a novel set partitioning formulation and a branch-cut-and-price algorithm to solve this problem. They assume the dependence between the fuel cost and travel speed is a strictly convex differentiable function.

Almost at the same time, Wen, et al (2017) also developed a branch and price algorithm and a constraint programming model for a multiple ship routing and speed optimisation problem under time, cost and environmental objectives. It is worth mentioning that this is the first time anyone had considered fuel consumption as a function of payload, fuel price as an explicit input, freight rate as an input and in-transit cargo inventory costs all together in a multiple ship scenario.

He, et al (2017) considered the fuel cost is a continuously differentiable and strictly convex function of the speed. They developed a simple and high efficient algorithm which is 20 to 100 times faster than a general convex optimisation solver on test instances and requires much less memory. This algorithm also helps shipping planners to achieve a better understanding of how to balance operating cost and service quality.

All above researchers made great contribution on voyage optimisation. However, several studies assumed the ship speed is fixed, while several studies also manually make a speed up or reduction with a certain speed step to see the benefits, they did not realise the automatic speed optimisation. Several studies also did not consider ship safety as a strict constraint when calculating the energy efficiency. Also most of voyage optimisation methods did not develop interfaces for newly introduced technologies, and therefore do not have the versatility of other new technologies. But the introduction of new technologies often affects the final optimum results, which often make designers to redevelop the optimisation algorithm. Another fact is that many studies have focused more on optimisation model or optimisation algorithm itself, while reducing the weight of the important influences brought by the weather. They often failed to give an appropriate voyage plan according to the weather conditions before ship departure. Although they do have more or fewer constraints, all of these studies provide very positive ideas and methods for voyage optimisation and especially speed optimisation in different shipping scenarios. There is a reason to believe that if combined with weather routing, the voyage optimisation must be able to provide more accurate ship operations strategy for practical shipping tasks with various objectives.

2.3 Applied algorithms for weather routing

Ship weather routing technology introduces the effect of weather conditions on voyage optimisation. Besides the quality of different types of data (the accuracy of ship hydrodynamics estimation and the quality of weather forecasting data), the optimisation algorithm also plays a key role in weather routing process. An optimisation algorithm with good applicability can not only leads to the best decision making for final optimal voyage plan, but also provides very high calculation efficiency for weather routing process. Several most common applied algorithms for weather routing are reviewed as below.

2.3.1 Calculus of variations

Calculus of variations is a field of mathematical analysis that deals with maximising or minimising functionals, which are mappings from a set of functions to the real numbers. Functionals are often expressed as definite integrals involving functions and their derivatives. The key theory of calculus of variations is solving Euler-Lagrange equations. In ship routing field, this method is usually applied by the minimum time routes optimisation through variation of the trajectory control parameters (Walther, et al, 2016). Hamilton, et al (1961) carried out two case studies with calculus of variations for minimum time ship routing: Case 1 assumed ship speed is primarily a function of position and case 2 assumed the ship speed is a function of its direction as well as position. In both cases the ship speed is time-independent, and he recommended case 2 is better for operational adaptation. Following Hamilton's work, Haltiner, et al (1962) solved the same problem by assuming the wave field is steady and using the stationary form of the Euler equation. Faulkner (1962, 1963) extended this theory by considering wave field as function of time. Bleick, et al (1965) moved forward to prove the numerical integrations involved in the theory of minimal-time ship routing through time-dependent wave fields are feasible and also three-dimensional interpolations in the wave field data is necessary. De (1968) applied Pontryagin's theory on optimally controlled processes to solve the least time track problem. Bijlsma (1975) also did a great job of solving least time tracks problem with calculus of variations and optimal control theory (Pontryagin's maximum principle). In his PhD research, he introduced a polar velocity diagram making the ship's velocity as a function of the angle between the ship's heading and wave direction when the ship position and transit time is fixed. He considered four necessary conditions from the classical calculus of variations (Euler-Lagrange, Weierstrass, Legendre and Jacobi) to find an arc furnishes a relative minimum for the aimed problem. A series of time fronts formed by a set of points reachable within a 6 hours or 12 hours' time step is constructed to get the final absolute minimum as shown in Figure 2.1. He also touched the minimum fuel consumption routing with the same theory in his thesis but explained in detail the whole computational method for this problem 25 years later (Bijlsma, 2001). This method can be even used for minimising discomfort of passengers or damage to cargo. He (Bijlsma, 2002) also obtained least-time routes with computational methods based on the maximum principle and corresponding continuous type of dynamic programming when ship routing is treated as a continuous process. Next, Bijlsma (2004) extended time-fronts methods used to the minimisation of fuel consumption and to examine the relationship between these methods and the energy-front method.

After that, he (Bijlsma, 2004) introduced limited manoeuvrability to minimum time/ fuel consumption routing which gives a more realistic picture to the ship navigation. Four years later, Bijlsma (2008) proposed a relatively simple and convenient for operational use method aimed at the reduction of the air pollution of ships. Still based on calculus of variations, this method was done by specifying the amount of fuel that can be consumed on a specific ocean crossing and by computing a minimal-time route for that given amount of fuel.

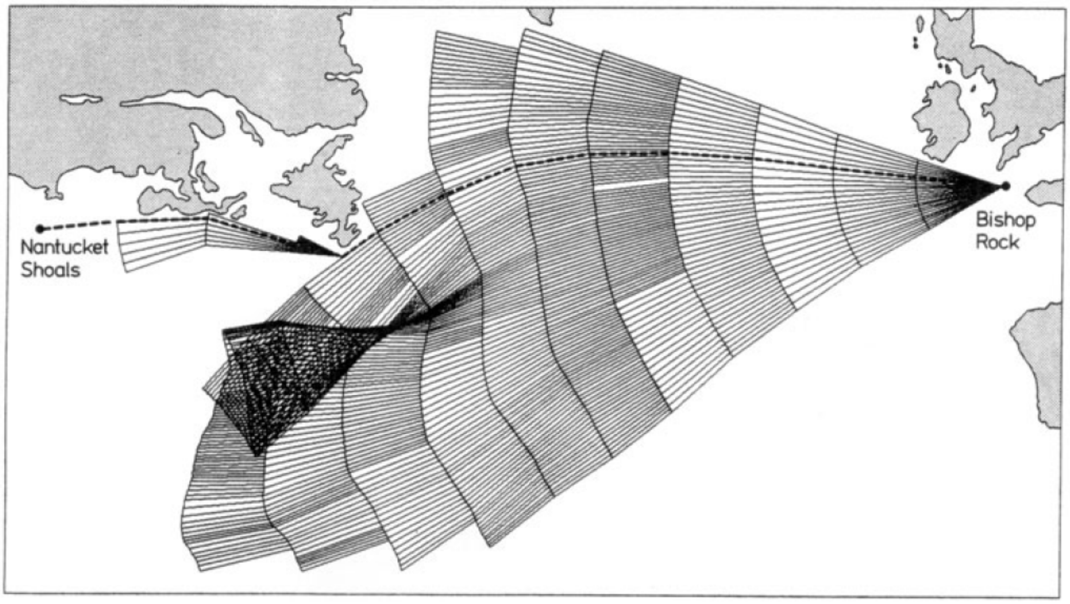


Figure 2.1 The least-time track (dashed line) (Bijlsma, 1975)

In essence, calculus of variations treats the ship routing as a mathematical problem and use optimal control theory to solve it. This method can provide insight into the nature of the routing problem and to some degree can be regarded as the basis of several other more advanced ship routing methods like Isochrone and Isopone which will be introduced below. The theoretical basis of calculus of variations is not simple and there is still scope to push that further. Some assumption and simplification are introduced in the calculating process. For example, the ship's speed is always assumed at maximum which is not reality. In terms of theory, due to some simplification, the numerical construction of time front or energy front may be incorrect. Furthermore, some inaccurate factor would be amplified by simplification when solving Euler-Lagrange equation, which sometimes creates unreliable results.

2.3.2 Isochrone method

The isochrone method is a classical method used in ship routing and even much commercial software, like OpenCPN (OpenCPN, accessed 2015) and QtVlm (QtVlm, accessed 2015), which was originally proposed by James (1957). It generates attainable isochrones (or time front) one by one repeatedly through varying ship headings and assuming constant engine power, which means setting several lines a ship can reach after a certain time from the departure (as shown in Figure 2.2). When an isochrones coincides with the destination port, a minimum time route can be easily determined. It is worth noting that, when the first isochrone is settled, the construction of the second isochrone will not only take into account the direction of ship travelling straight ahead, but also the direction perpendicular to the first isochrones. However, the original isochrones method has a disadvantage of “isochrones loops” when it is applied in computer programs (Szlapczynska, et al, 2007). Here, “isochrones loops” means the isochrones are in irregularity shape caused by non-convexity of speed characteristic for given weather condition. This problem makes the method cannot generate accurate enough isochrones.

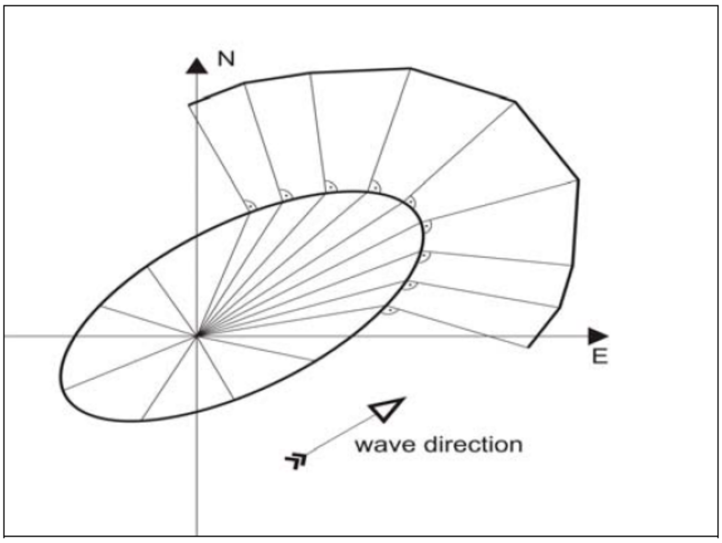


Figure 2.2 Construction of the first and second isochrone (Szlapczynska, J. 2007)

Hagiwara (1987, 1989) developed a modified isochrones method more suitable for computer programming. This method is applied to minimum time/fuel consumption routing considering both deterministic and stochastic routing. The GCR (Great Circle Route) between departure and destination is taken as reference together with several GCRs from the initial point at slightly different angles as shown in Figure 2.3. This practice forms more reasonable isochrones and definitely extends the selectable range of optimal results thereby generates more accurate result. For deterministic routing, it is assumed that the forecasted environmental conditions are strictly correct and the ship's speed, drift angle, rudder angle, heel angle and engine power can be predicted accurately. However, in reality, the environmental conditions are always not perfect, so that these performances like ship's speed, ship's motion and engine power which are closely related to forecasted environments will also involve errors. An imperfect mathematical modeling also causes these errors. Therefore, for stochastic routing, the standard deviations of passage time, fuel consumption, average speed as well as the covariance matrices of ship's positions are estimated based on the information of the errors related to forecasted environments. By using this method, the degree of uncertainties is quantified, and then the mathematical model is improved. It is easier to plan the operation schedule of a ship and to determine a margin for fuel oil to be loaded. However, the modified isochrones method also has the disadvantage that the propeller rotation speed is assumed constant, which always make the minimum fuel consumption route only suboptimal.

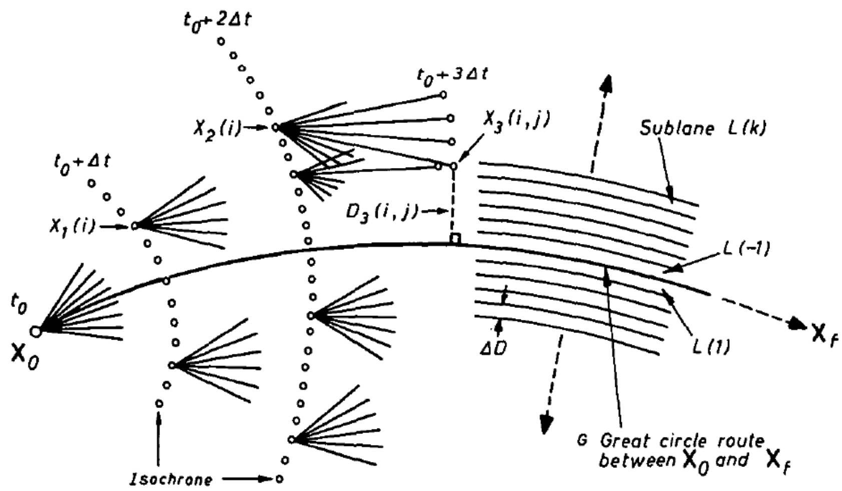


Figure 2.3 Modified isochrones method (H.Hagiwara, 1987)

Lin, et al (2013) developed a three-dimensional modified isochrones (3DMI) method utilising the recursive forward technique and floating grid system for ship weather routing as shown in Figure 2.4. This method allows the ship speed and wave heading angle to vary with geographic locations (three dimensions). The floating grid system is employed to define the spatiotemporal layouts for ship routing optimisation while the recursive forward method is applied to assign the weight factor at a stage between two isochrones. Here, the weight means voyage progress which can represent passage time, fuel consumption, structural damage, ship motions and even arrival time, so the optimisation problem can be transformed to find the minimum weight of these states. This method also strictly considered seakeeping characteristics and the added resistance for evaluating the ship routing based on the 6 DOF mathematical model of ship hydrodynamics, which makes the final optimal result more reliable.

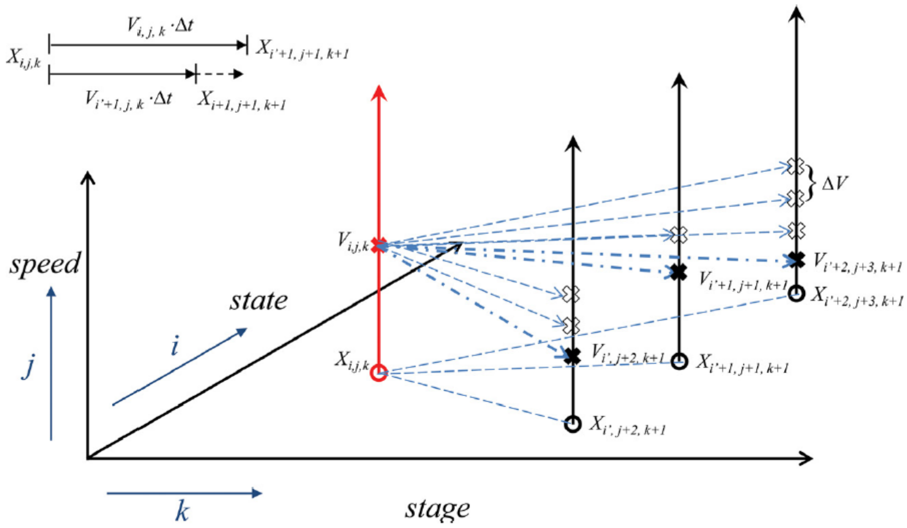


Figure 2.4 The schematic diagram of three-dimensional modified isochrones method (Lin, et al, 2013)

2.3.3 Isopone method

The principle of Isopone method (Klompstra, et al, 1992; Spaans, 1995) is similar to Isochrone method. It defines the attainable shipping boundary as an isopone with equal fuel consumption instead of sailing time in a three-dimensional space (geographical position and time). At the beginning, the first isopone is defined as the set of attainable points from the initial point with a fixed amount of fuel and varying ship course. Next, all these points on the first isopone are regarded as initial points for calculating the second isopone. For every point on the first isopone, an energy fronts can be determined and the envelope of all these energy fronts is defined as the second isopone. It can be extended to three dimensions as shown in Figure 2.5. This procedure continues for subsequent isopones until an isopone crosses the destination. Here, in the final step, the amount of fuel is adapted to make the final isopone crosses the point of destination at the aimed ETA on the time axis. Finally, the minimum fuel route can be obtained by tracing back the control variables (headings and speeds) used to reach the point on the isopone tangent to the time axis at the point of the corresponding destination in every stage. This method is similar to dynamic programming theory as it employs the forward recursive algorithm, but has led to moderate improvements in the calculation efficiency.

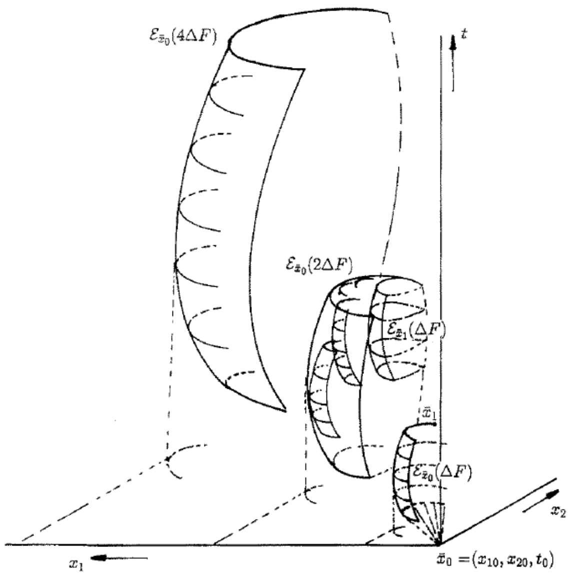


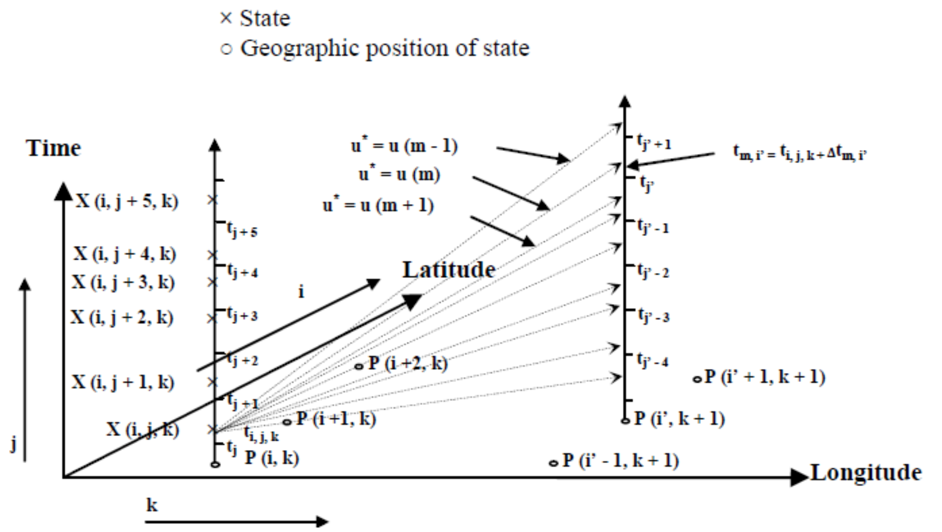
Figure 2.5 Isopones in a three-dimensional state space (Klompstra,1992)

2.3.4 Dynamic programming

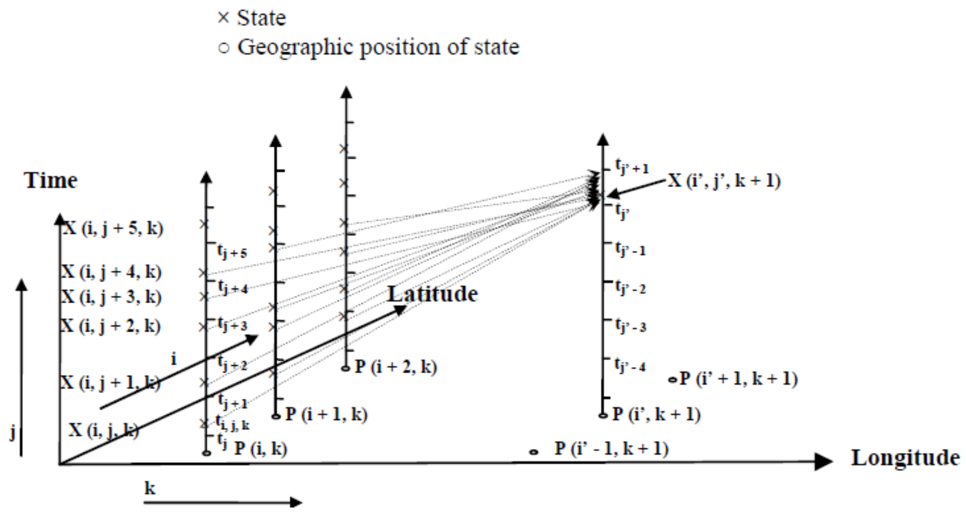
Dynamic programming method is developed based on Bellman's principle of optimality (Bellman, 1952, 1957). Dynamic programming algorithms are often used for optimisation. A dynamic programming algorithm firstly breaks a complex problem down to several simpler subproblems, and then these subproblems will be solved. With the combination of their sub solutions, a global best solution for the given problem will be obtained. In weather routing, the subproblems are sub-routes, which are usually represented by "stages". Stages must be determined by monotonically increasing variables like time or distance in routing problem. Two characteristics are introduced to express one stage. The first one is a control variables which can be ship's heading or speed and the other one is the states which describe the geographic position or even local time of a ship. The subproblem is to calculate the optimal control variables among various states in one stage. The results obtained from the previous stage will be used in the calculation of the next stage. The whole calculation will carry out this procedure stage by stage with backward or forward recursive algorithm until an optimal voyage plan is determined.

Chen (1978) summarised a dynamic programming approach with a backward recursive algorithm to the problem of minimum cost ship routing under uncertainty. De Wit (1990) employed the dynamic programming method for solving the minimum propeller rotating rate problem based on a fixed time ocean route with a prefixed grids system. In his research, the propeller rotating rate was assumed constant during sailing. Calvert, et al (1991) used the same method for minimum fuel consumption routing problem on a trans-Atlantic passage. He presented a model to predict the motion response of ships based on the weather forecast and the engine power is set as constant during his calculation. More detailed and extended research was presented in his PhD thesis (1990). Similar to Chen, Calvert (1990) also selected vessel distance as the stage variable and adopted backward recursive algorithm in dynamic programming. As the ship's heading is the only control variable, they only needed to take into account two dimensions: latitude and longitude for a state in sub routing problems. So this method can be also regarded as a 2-dimensional dynamic programming (2DDP) method.

Aligne, et al (1997, 1998) presented a time/fuel minimisation algorithm for ship weather routing based on dynamic programming with the forward recursive algorithm. They employed time as the stage variable and more importantly, they tried to consider two control variables of both engine power and shipping course during dynamic programming procedure. Based on above, Shao (2012, 2013) developed a 3-dimensional dynamic programming (3DDP) method for ship weather routing problem, which contains 3-dimensional variables: latitude, longitude and time for a state, and uses a forward algorithm in the optimisation process as shown in Figure 2.6. As he mentioned in his PhD thesis, a forward algorithm has a better performance than a backward algorithm for weather routing problem. Because the initial departure time is always fixed while the arrival time at a current location usually varies corresponding to different minimum fuel consumption. This logic is easier to be understood and certainly offers more convenience in programming. By extending the states to three dimensions, the method can consider both ship's heading and speed as the control variables, so it can provide much better shipping voyage plans. Shao tested this method on minimum fuel consumption routing problem and received very good results. He even developed an effective weather routing tool called ITEES (Intelligent Tool for Energy Efficient and low environment impact Shipping) based on this method at last.



(a) Calculating the possible states of stage k+1



(b) Determining the state

Figure 2.6 Schematic diagram of the 3DDP method (Shao, 2013)

Furthermore, Avgouleas (2008) utilised an algorithm of Iterative Dynamic Programming (IDP) which is developed by Luus (2000) for minimum fuel consumption routing problem. The conventional dynamic programming algorithm always required a fine grid of states to ensure the global optimum convergence. This makes the feasibility of the algorithm extremely sensitive to the dimensionality of the problem. When the algorithm meets problems of high dimension, which is also known as the curse of dimensionality, it will become impractical for use due to the increasing computation time. To overcome this shortcoming, IDP uses a single grid point instead of a complete grid of admissible states. The procedure starts with an initial guess for the optimal control and then carries out similar standard DP algorithm iteratively. An optimal control policy is obtained within each iteration. The next iteration improves the solution by refining the granularity of the quantised allowable controls based on the previous iteration. Finally, the minimum fuel consumption voyage plan can be obtained by iteratively optimising both ship's heading and speed.

More recently, the DP algorithm to some degree becomes a most popular method used for weather routing problem due to its expandability. However, most of the researches still highly depend on the grids system. With a predefined grids system, it is easy to handle the impassable shipping area by moving, adding and deleting grid points, but it also makes the accuracy of the result highly dependent on the grid fineness (Simonsen, 2015). The selection of discrete grid systems still needs to get more attention (Motte, R.H. 1990).

2.3.5 Dijkstra's method

Dijkstra proposed the basic theory of this method in 1959. This method originally aims to find the path of minimum total length between the n nodes connected in a graph so that it can also be regarded as a kind of graph searching optimisation method. Many extension and modification of this method have been developed for solving different type of practical problems since then. Regarding weather routing, a network connected by n nodes should be built based on grids system before optimisation, and then positive weights, which represent passage time, fuel consumption or other variables, are assigned to the graph edges. By analysing the sum of weights on this network, the optimal route with different objectives can be determined (as shown in Figure 2.7).

Bottner (2007) applied a multi-objective Dijkstra's algorithm to a graph of feasible lines in order to solve the two objectives (shortest route and shortest possible time period) weather routing optimisation problem. Panigrahi and Umesh (2008) chartered minimal time route by using Dijkstra's method over the Arabian Sea with third-generation spectral wave model WAM. Padhy, et al (2008) also obtained reliable optimum route with Dijkstra's path optimisation scheme based on the wave height information from GEOSAT altimeter records in consideration of voluntary speed reduction. Takashima, et al (2009) applied Dijkstra's algorithm to calculate an optimum minimum fuel route suitable for coastal merchant ships using the precise forecasted environmental data and the propulsion performance data of the ship on actual seas. Sen, et al (2010) made some new developments for minimum time routing problem still based on Dijkstra's method. They still gathered the wave data for the North Indian Ocean region from WAM model, but they considered more realistic constraints like land boundaries, non-navigable water, effects of wind and current etc. in ship routing process. More recently, Mannarini, et al (2013) presented a prototype for an operational ship routing decision support system based on a modified Dijkstra's algorithm using time-dependent environmental fields. The shortest route is obtained with the implementation of safety restrictions for avoiding surf riding and parametric rolling according to IMO guidance. Eskild (2014) also took a study about the application of Dijkstra's algorithm on ship weather routing, she used this algorithm to solve the minimum fuel routing problem. She also attached the Matlab codes for ship routing problem in her master's thesis which is very helpful for the same type of research. In 2015, Sen, et al once again retrieved minimum-time route over North Indian Ocean with a form of Dijkstra's algorithm. This time they developed a versatile algorithm which almost considered all practical constraints that a ship may face during her voyage. They also took into account both involuntary and voluntary speed reduction to determine the weight functions. Besides, Chu, et al (2015) researched the impact of meteorological and oceanographic (METOC) ensemble forecast systems on minimum fuel consumption routing for navy vessels with the Dijkstra's method.

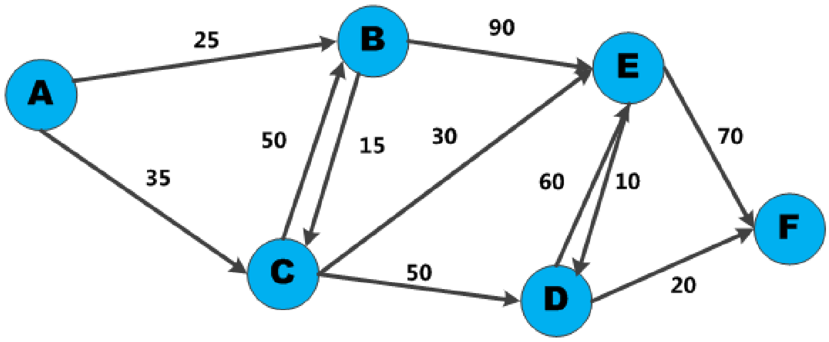


Figure 2.7 An example of Dijkstra's Method

Although the Dijkstra's method is easy to be understood and can always provide the satisfactory route according to users' requirement, it still has some disadvantage. This method has high grids dependency, which not only makes the result highly dependent on the grids resolution but also may result in the optimal route which is not smooth enough. Besides, during the route optimisation, the engine power is always set to constant and in most cases, only one object can be optimised with the Dijkstra's method.

2.3.6 DIRECT method

The DIRECT method was first developed by Jones, et al (1993) for finding the global minimum of a multivariate function subject to simple bounds. It is a modification of the standard Lipschitzian optimisation with Shubert's algorithm. In standard Lipschitzian approach, a Lipschitz constant should be specified to determine how much emphasis the optimisation will place at the global level versus local level. The new algorithm does not need to consider that as it searches optimal result at both global and local level directly and simultaneously. Therefore it converges much faster towards solution fields and becomes much easier to set up as fewer parameters need to be adjusted.

The name DIRECT stands for DIviding RECTangles, but also captures the fact that it is a direct search technique (Brise, 2008). The algorithm uses an n-dimensional hyper-cube domain to represent n variables in the optimisation problem. Firstly, the algorithm sets a sample point in the search domain, and then it will iteratively split the domain from this sample point as the optimisation is processed. For the initial division in each iteration, it always splits the current domain into three same sizes of hyper-cubes as shown in Figure 2.8. All the information in the centre point of each hyper-cube will be collected to compute the objective function and also be used to determine if this domain should be subdivided in the current iteration. This process is computed repeatedly until the optimal result is obtained. Based on the above, Finkel (2003) proposed a user guide to explain further how the DIRECT optimisation algorithm solves different type of problems.

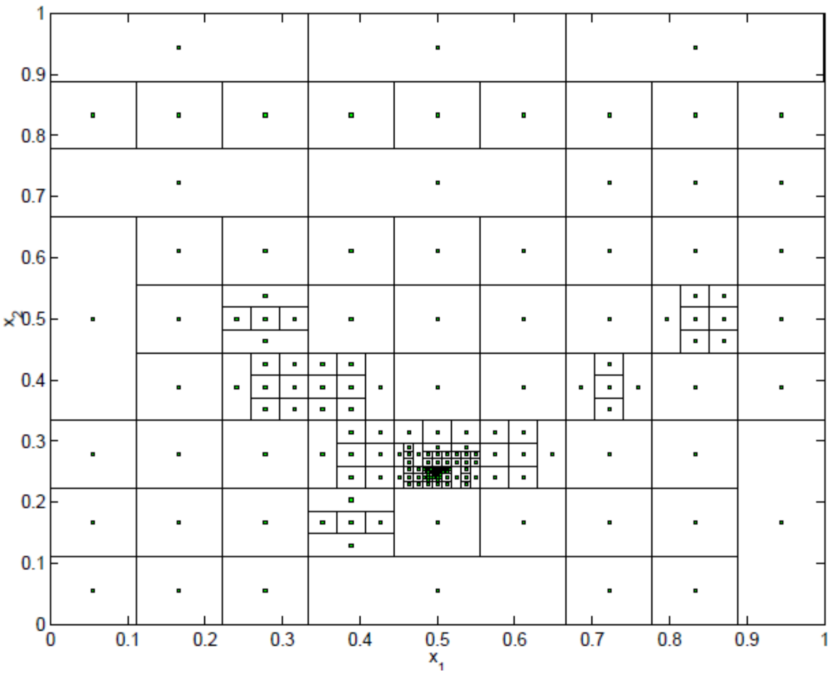


Figure 2.8 Illustration of the DIRECT method after several iterations (2-dimension) (Finkel, 2003)

This method was introduced to solve the weather routing problem by Larsson and Simonsen (2014, 2015). They developed a novel ship weather routing program based on the DIRECT algorithm. Several simple test cases were carried out to evaluate the capabilities of finding shortest route, avoiding obstacles, avoiding storms by speed optimisation, utilising weather condition for minimising fuel consumption and their combinations. The DIRECT algorithm has rapid global convergence and does not rely on the grids system much in weather routing problem. However, their model did not build a special weather data access module and simplified the ship safety calculation by setting a maximum value of wave height. Also the DIRECT algorithm often needs longer time to find local optimal route and when the dimensional of variables is high, it will increase the complexity of optimisation process rapidly. Furthermore, this method is only applied to ship weather routing problem at very preliminary stage, there must be more development space in the future under the consideration of more practical conditions and combination with other algorithm etc.

2.3.7 Evolutionary algorithms

An evolutionary algorithm is a global optimisation method inspired by biological evolution. The evolutionary process is stochastic. At the beginning, the algorithm generates an initial population of solutions randomly. And then this population will create further generations by the ways of reproduction, mutation, recombination or natural selection. A fitness value, as the only evaluation index is assigned to each individual in the population. Individuals with higher fitness values have a greater chance of becoming parents for creating next generation than those with lower fitness values. Through continuous iterations, when the computation is converged or reaches to the pre-configured maximum number of generation, the individual with the maximum fitness within the evolutionary process will be selected as the optimal solution. Evolutionary algorithms particularly fitted well with multi-objective optimisation problems. For multi-objective optimisation problems, a solution may be good for a particular target, but it may be poor for others, so there is a set of compromised solutions named as Pareto-optimal set or nondominated set. The evolutionary algorithm achieves a global search by maintaining a population composed of potential solutions between generations. This population-to-population approach is useful for searching the Pareto optimal solution set for multi-objective optimisation.

Evolutionary algorithms are very common methods applied in ship weather routing for solving its multi-objective optimisation problems, in which the multi-objectives can be arrival time, fuel consumption, cost and safety etc. The candidate routes are evaluated by a fitness value in view of ship sailing, design and optimisation criteria. Harries and Hinnenthal, et al (2003, 2008) adopted the multi-objective genetic algorithm (MOGA) to obtain minimum fuel consumption route with the desired arrival time in consideration of safety constraints. The typical Pareto frontier for two objectives routing: ETA and Fuel is shown in Figure 2.9. Similarly, Marie, et al (2009) applied MOGA and automatic meshing method to minimise fuel consumption for motor vessel routing. Szlapczynska (2007) utilised Isochrone method in modern weather routing evolutionary systems for an initial population of routes and made these routes are free from land crossings. After that, Szlapczynska, et al (2009, 2013) proposed a Multicriteria Evolutionary Weather Routing Algorithm (MEWRA) and preliminarily applied it to the hybrid propulsion ship model. The solution utilises two basic multicriteria mechanisms, namely multicriteria evolutionary algorithm - Strength Pareto Evolutionary Algorithm (SPEA) and multicriteria ranking method - Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (Fuzzy TOPSIS). Krata (2012) introduced a new measure of safety refers to dynamical phenomena taking place in rough sea conditions for MEWRA. More recently, Szlapczynska (2015) upgraded the MEWRA method by using the Zero Unitarization Method instead of Fuzzy TOPSIS as the ranking method. The presented approach offers fully customizable support to multiple criteria and constraints so that it is effective to obtain significant reductions of passage time, fuel consumption and risk factor with MEWRA. Maki, et al (2011) considered the weather routing problem as a multimodal function problem and they proposed a multipoint search method - real-codes genetic algorithm (RCGA) to obtain the optimal route towards two objectives: fuel efficiency and ship safety in parametric rolling. Andersson (2015) employed a modification method of the Distance based Pareto Genetic Algorithm (DPGA) for three-criteria multi-objective weather routing problem. The objectives considered are travel time, fuel consumption and wave height (which is a simple criterion to ensure safety). He proved the modified DPGA can make the computation much faster than the grids search method without loss of results' quality. Moreover, Vettor, et al (2016) also developed a multi-objective weather routing system based on the combination of the upgraded Strength Pareto Evolutionary Algorithm, the grid-based Dijkstra's algorithm and the Hyperplane Strategy Distance (HyStraD) ranking method. They deeply analysed the impact of different parameters on the accuracy of shipping optimisation, e.g. sea-keeping criteria or user preferences, and optimisation settings, such as the number of iterations, operators of crossover and mutation.

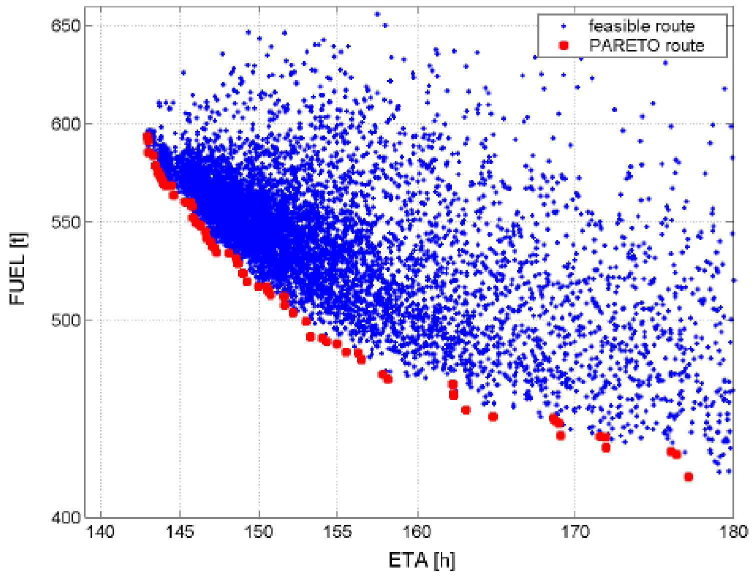


Figure 2.9 Pareto frontier for two objectives routing: ETA and Fuel (Hinnenthal, 2008)

An evolutionary algorithm is ideal for multi-objective optimisation of ship weather routing problem. The entire optimisation process can be monitored and it is easy to be integrated with other weather routing or optimisation algorithms. However, the number of parameters used in the evolutionary algorithm is a few more than other algorithms which increase the complexity of the optimisation procedure and makes the results very sensitive to the parameter settings. The evolutionary algorithm may converge to local optimal and cannot achieve global optimal in the case of improper selection of fitness function.

2.4 Ship routing services

As the benefits of ship routing technology are increasingly noticed and recognised, marine agencies and commercial establishments from all over the world have developed many effective and efficient commercial ship routing services. There exist three types of ship routing services in the market which can fall into on-shore, onboard and combined on-shore and onboard services. The on-shore based routing systems, as the name implies, suggest an optimum route plan computed in a shore-based centre and send it to the ship by wireless communication. Ship operators do not participate in the calculation of the optimal route but would use the result as a reference to decide to which extent this proposal will be followed (Spaans, et al, 2000). The onboard based routing systems provide, in a sense, a real-time service to users. It always works together with the vessel performance monitoring devices and other information collection equipment. Ship operators collect the real-time weather information and ship performance and then use them in the optimum route calculation on board. Therefore, the ship can always follow the continuously updated voyage plan at the first time. The combination of on-shore and onboard systems have both their advantages and provide users with better services through the information interaction process between shore and ship.

Generally, these ship routing services are developed for avoiding adverse weather and “No Go” area, minimising transit time, minimising fuels consumption and minimising the risk of damage to the vessel, crew and cargo. Some other considerations might include passenger comfort or schedule keeping. Most of the time, the goal is to find the best balance to these requirements. In addition to weather routing, these services can also be expanded to utilise in marine weather forecast analysis, vessel performance monitoring and voyage reconstruction.

Hinnenthal (2008) has made an overall review of the existing routing service and decision support systems as shown in Table 2.1. The software from various countries covers different functions distributed in the weather forecast, route planning, route optimisation, warning system, ship monitoring, data recording and vessel tracking.

Table 2.1 Exemplary compilation of routing service or decision support systems (Hinnenthal, 2008)

Service provider	System	weather forecast	route planning	route optimisation	warning system	ship monitoring	data recording	vessel tracking
Aerospace and Marine International (USA)	Weather 3000, internet service, maps displaying fleet and weather information	X					X	X
Applied Weather Technology (USA)	BonVoyage System, on-board system	X	X					
Deutscher Wetterdienst (Germany)	MetMaster, MetFerry, ashore routing systems, advice on demand		X	X				
Euronav (UK)	seaPro, on-board system, software or fully integrated bridge system	X	X				X	
Finish Meteorological Institute (Finland)	weather and routing advice from ashore for the Baltic sea	X	X					
Fleetweather (USA)	meteorological consultancy from ashore	X	X					X
Force Technology (Denmark)	SeaSense, real-time on-board decision support system managing wave-induced structural loads and ship motions				X	X	X	
Germanischer Lloyd, Amarcon B.V. (Germany, Netherlands)	Shipboard Routing Assistance System SRAS	X	X		X	X	X	
Meteo Consult (Netherlands)	SPOS, on-board routing system	X	X	X			X	
Metworks Ltd. (UK)	meteorological consultancy from ashore	X	X					
Norwegian met office, C-Map (Norway, Italy)	C-Star, on-board system	X	X					
Oceanweather INC., Ocean Systems INC. (USA)	Vessel Optimisation and Safety System, VOSS, on-board system	X	X	X	X			
Swedish met and hydrology institute (Sweden)	Seaware Routing TM, Seaware Routing Plus TM and Seaware EnRoute Live TM, on-board systems, and support ashore	X	X		X	X	X	
US Navy (USA)	STARS, on-board system	X	X	X		X		
Weather News International, Oceanwaves (USA, Japan)	Voyage planning system VPS and ORION, combination of ashore and on-board routing and optimisation software	X	X	X				
Weather Routing Inc. (USA)	Routing advice from ashore and Dolphin navigation program combined with a web-based interactive site	X	X					
Transas (UK)	Ship Guard SSAS, on-board system, software or integrated to bridge system	X	X			X	X	X

Among them, the Ship Performance Optimisation System (SPOS) from the Netherlands, BonVoyage weather data System (BVS) and Vessel Optimisation and Safety System (VOSS) from the USA are the three most popular systems.

SPOS is the world's leading onboard weather routing system developed by Meteo Consult. "SPOS is designed to enable captain and crew to adjust the route calculations depending on the weather information provided and the ship's specific characteristics. The captain can then chart the optimum route (both in terms of safety and efficiency) for his ship in prevailing conditions. (Meteo, accessed 2017)" The key benefits of SPOS include reliable weather data, efficient voyage and ETA planning, saves fuel and time, easy tool for comparing speed and route alternatives, increased safety level for masters and crew, implementation in SEEMP regulation and 24/7 weather operations support. BVS is an easy to use graphical marine voyage optimisation system developed by Applied Weather Technology (AWT) - a StormGeo company. BVS has an improved optimisation algorithm along with a customizable speed vs consumption curves that deliver more accurate estimates of fuel cost and time en-route. Based on a weather data display package, both weather-induced constraints and no-go areas can be considered for each particular voyage. It has been used by more than 5,500 vessels in the world. The latest version is BVS 8, which has a comprehensive upgrade on seakeeping prediction, motion sensor capability, anemometer integration, position polling, system compatibility, tropical storm data updating, ship specific consumption curves and dual speed optimisation (Weber, 2007; StormGeo, accessed 2017).

As for other software listed in Table 2.1, Vessel Optimisation and Safety System (VOSS) from the USA used to be a very classical service. VOSS integrated all shipboard navigation, passage planning and real-time monitoring subsystems into a complete system that monitored the current ship operating status. It had a shipboard weather station and could provide optimum ship routing and seakeeping decision support. It could help to decrease voyage costs and reduce the risk of vessel and cargo damage and loss. VOSS Vessel Performance Analysis routines have been used at American President Lines, Ltd., American Ship Management, Matson Navigation Company, and Chevron Shipping Company (Chen, et al, 1998; U.S. Department of Transportation, 1999).

In modern times, there are many other intelligent ship routing software that is widely used in marine transportation. Some of them are introduced below.

The AdrenaShip software (Adrena, accessed 2017) developed by Adrena company is another effective tool to help crews make better navigational decisions. It has four main features: data analysis, real-time and simulated ETA calculation, coastal routing and ocean routing. Among them, ocean routing is the ideal solution for trans-ocean commercial vessels routing. It automatically avoids the coasts and suggests a range of different courses, together with their respective fuel consumption and ETA. And then it considers both weather impact data and the vessel's fuel consumption tables to obtain the best course. It also takes into account navigation rules in terms of speed, course and restricted zones for certain types of fuel (Adrena, accessed 2017). AdrenaShip not only saves on fuel consumption but also improves route planning and increases passage safety.

OpenCPN (Chart-Plotter Navigation) is free chart plotter (OpenCPN, accessed 2015) and GPS navigation software developed by a team of active sailors using real-world conditions for program testing and refinement. OpenCPN has the feature that it achieves a variety of functions by many plugins. These plugins include AIS/Radar view, various chart support, logbook and voyage data recorder, navigation safety and weather routing modules etc. Another feature is that OpenCPN is open source software. Every experienced manager could edit it according to their personal preferences. This feature can also provide its open codes as a reference for the design of other ship routing software. Now OpenCPN is supported by more than 20 languages.

QtVlm (QtVlm, accessed 2015) is navigation software originally designed for virtual and real sailing boats. It is also a free weather GRIB viewer that accepts all kinds of GRIB files. It has similar functions to OpenCPN and is also open source software. It can communicate with OpenCPN; operators can import and export routes between each other.

Optimum Voyage Routing (OVR) service was developed by Aerospace & Marine International (AMI) which has been providing weather services to the maritime industry since 1991 (Aerospace & Marine International, accessed 2017). OVR can help ship operators select most favorable and economical routes that meet the shipping schedules and have the lowest risk of weather damage in the overall consideration of the weather impact, fuel cost, daily hire rate, cargo and time constraints. It provides full range of services including pre-departure route recommendation, daily voyage monitoring, en-route weather advisories, route recommend updates, aurora global fleet manager, en-route performance speed calculations, en-route ETA calculations, email fleet status report and end of voyage report (Aerospace & Marine International, accessed 2017; Keith Thomson, 2011).

FastSeas (Fast, accessed 2017) is a weather routing and passage planning tool. It will calculate the fastest route to take users from point A to point B given the current NOAA GFS weather forecast, current oceanic currents, the performance of user's vessel, and user's comfort criteria (FastSeas, accessed 2017).

In addition to those services for commercial ship routing, there are also many small, smart, effective and professional routing software for boat racing, sea fishing and even yacht recreation. Some of them are introduced alphabetically below.

Bluewater Racing (Bluewater Racing, accessed 2017) is a free program that provides strategic tools for long-distance Yacht Racing and Cruising. It is easy to build, display, and edit multiple routes. It provides powerful route optimisation and powerful support for weather data.

Deckman (B & G, accessed 2017) is Tactical PC-based software for race winning. For either offshore or inshore, Deckman could provide optimum routing, live updates and competitor handicap to help navigators plan race-winning strategies.

Expedition (Expedition, accessed 2017) has been in development since the mid-1990s by veteran Volvo Ocean Race navigator and Whitbread winner Nick White. Expedition has been used in multiple Volvo Ocean, America's Cup and Grand Prix events and is the most advanced and usable navigation software available for racing around the world or some local harbor (Expedition, accessed 2017).

Maxsea Timezero (Timezero, accessed 2017) is a full marine navigation software solution for recreational sailing and motorboat users or professional navigation. It has many professional versions like TZ Navigator, TZ Professional, TZ Charts, TZ Coastal Monitoring and TZ App. Users can choose the product that better suits his need. It now has more than 2500 TZ navigator users.

SailFast™ (SailFast, accessed 2017) is a PC-based navigation program that greatly enhances sailing decisions aims to go fast and win races or to cruise off-shore safely. Users can derive optimum routing solutions by analysing GRIB file weather and ocean forecasts and using the boat's polar. It provides the interface to GPS and other boat instruments.

ScanNav (ScanNav, accessed 2017) is a French company providing cartographic and navigation software assisted by GPS to a variety of customers. The software also uses the same name and provides all necessary tools and support for ship navigation and ship routing. Its features include: free and sustained ocean currents and waves provision to feed ship routing software; high-quality information allowing consistent fuel saving and lower CO_2 emission; more accurate planning of arrival time; safer sailing routes for human beings and boat equipments.

Squid is marine weather software (Squid, accessed 2017) which enables its users to prepare the weather for a race or a cruise. It enables them to download a lot of meteorological information according to the subscription. This tool enables users to calculate a route based on the forecast weather**.**

Raymarine RayTech™ Navigation Software (Raymarine, accessed 2017) is designed for trip planning and navigation needs. It can be installed on a PC onboard and create and plan routes by accessing radar, digital sonar, charts and navigation data and their compatible multifunctional displays.

WeatherNet (Ocens, accessed 2017) also provides a very good tool for weather and ocean analysis, route-finding and most importantly safe and efficient travel at sea.

Furthermore, some small routing App used in smartphone or tablets are also very popular:

AVALON navigation systems (Avalon, accessed 2017) is a straightforward and complete weather routing and navigation system on a tablet. It provides the services including weather routing, integrated nautical maps, navigation and route monitoring and even some racing option “on demand”.

Nobeltec TimeZero (Nobeltec, accessed 2017) is a marine navigation App specially designed for coastal sailors featuring the most cutting-edge and useful tools & data. Its features are outdoor use on small boats and best for coastal sailing used on iPad.

PredictWind (PredictWind, accessed 2017) is another popular App for watercraft racing which has world-leading high-resolution wind forecast. It is powerful in departure planning and weather routing and has already been proved in Ocean Racing & Americas Cup.

SailGrib WR (SailGrib, accessed 2017) is a detailed and complete information loaded App designed for weather routing. It includes the features: a very powerful and easy to use weather routing module; a navigation module with AIS data; free download of all NOAA marine raster charts; atlases of tidal currents for all European coasts.

The APP4NAV company develops weather 4D (APP4NAV, accessed 2017) for boating and outdoor recreation. Its pro and further versions provide navigation and routing services associated with weather predictions. It has an advanced application of GRIB files weather forecast and routing for marine navigation.

Every commercial software on the market has its own characteristics. However, most of them are only applicable to coastal routing and they have only simple objectives, such as avoiding bad weather, ensuring ETA, and choosing the safest route for navigation. Calculating these objectives often does not use overly complex routing strategies. Few software can simulate ocean voyages and consider shipping energy efficiency, but they often just use the fuel consumption table or the speed vs fuel consumption curve to calculate the consumed fuels. Besides, these kind of software tend to be costly that may prevent some companies utilising them. And they always need to process a lot of data such as the data from the ship monitor devices. Furthermore, the availability of PC based systems is often limited which cannot meet some of special needs of ordinary users. Therefore, it is necessary to develop simple, efficient and highly versatile ocean navigation simulation software, and integrating more advanced optimisation algorithms in it to carry out shipping energy efficiency optimisation by office staff using desktop computers.

2.5 Wind assist technologies

Nowadays, in order to counter fuel price rising and tackle global warming, shipping industry makes great effort to find measures to increase fuel efficiency and reduce carbon emissions from ships. It is well known that compare to traditional fossil fuel, wind energy is extremely clean, free and abundant. Therefore, as a tendency of low carbon economy development, shipping with wind assist technologies is attracting more interest from shipping industry. Several most common wind assist technologies for shipping are reviewed as below.

2.5.1 Flettner rotor

The research in this study focuses on one of effective wind assist technologies-Flettner rotor. The main structure of a Flettner rotor consists a smooth cylinder and disc end plates on it that rototes around the long axis of the cylinder during operation. It uses Magnus effect for an aerodynamic force generation in the third dimension when the air passes across it at right angles (Seifert, 2012). A rotor ship is a type of ship designed to use the Magnus effect for propulsion (Betz, 1925; Nuttall, et al, 2016). The ship is propelled, at least in part, by large vertical rotors. German engineer Anton Flettner was the first to build a ship which attempted to tap this force for propulsion in 1920s, so Flettner rotors are also named after their inventor. Rizzo (1925) discussed the fundamental principles of the Flettner rotor ship in the light of Kutta-Joukowski theory. Actually, this technology is treated indifferently since it was first deployed. But these years, with the development of technology and proposition of "low carbon shipping" concept, people are turning their attention back to rotors as an immense potential measure (Howett, et al, 2015). They made many achievements on Flettner rotor technology. In 2008, the German wind-turbine manufacturer Enercon launched a new rotor ship, E-Ship 1 (as shown in Figure 2.10) and claimed that it can save up to 25% fuel compared to same sized conventional vessels after 170,000 sea miles in 2013 (Enercon, 2013). In 2014, Norsepower Company developed a "Norsepower Rotor sail solution" which is a modernised version of the Flettner rotor (Norsepower, 2014). They installed two Norsepower Rotors on a RoRo vessel "M/V Estraden" in 2014 and later 2015, and announced that this technology has potential for fuel savings of up to 20% for vessels with multiple, large rotors traveling on favourable wind routes (Norsepower, 2016). In 2016, the Viking Line company also considers the rotor concept for their next planned new building. They showed a new 63,000 GT vessel with large Flettner rotors which could help the ship to save up to 15% fuel consumption (Viking Line, 2016). This company also owns a famous cruise ship called MS Viking Grace, which was retrofitted with single Flettner Rotor. Besides, Traut, et al (2012) assessed the wind power performance of a bulk carrier fitted with three Flettner rotors on the route from Brazil to UK and suggested possible fuel savings of 16%. They also (2014) researched the average power contribution from the Flettner rotor on the analysed routes ranges from 193 kW to 373 kW. When three Flettner rotors are fitted on a 5500 DWT cargo carrier, they could provide more than half of the required main engine power under slow-steaming condition. De Marco (2016) analysed the Flettner rotor performance with the method of unsteady Reynolds averaged Navier-Stokes simulations and also presented the applicability of such device for marine applications.

Figure 2.10 “E Ship 1” from Germany (Craft, et al, 2014)

2.5.2 Dyna Rig (Sails)

The concept of Dyna Rig was first proposed by Wilhelm Prolss, a German engineer living in Hamburg (Perkins, et al, 2004). The Dyna Rig sail system contains a self-sustained main mast, and several horizontals curved yards are affixed rigidly to the mast. Its sail consists of a large number of canvas panels, each them can be regarded as a sub-sail. The main mast is rotational, and each sub-sail can be also adjusted individually according to the wind condition. When these sub sails are fully deployed, they will form a complete panel without any gaps to capture the wind. The Dyna Rig sail system can provide twice the efficiency of a traditional square rig system (Trouvé, et al, 2013).

There are four typical types of Dyna Rig sails, they are respectively Sail profile, Furlable panels, 360-degree rotational mast and Sais stiffness. Each of them has its own advantages, but the common advantage of them are that they can return very substantial energy efficiency benefits when the ship sails with downwind especially for a long voyage and they are easy to use that the automated Dyna Rig sailing systems can even greatly reduce the number of operational crew on ship (Trouvé, et al, 2013; Magma Company, 2018). A number of studies have been carried out to assess the performance of Dyna Rigs. Schenzle (1976, 1983) studied the sailing speed and the design of wind aid propulsion ships fitted with Dyna Rig in the 1980s. Dijkstra, et al (2000, 2003 and 2004) studied the application of Dyna Rig on yachts and made recommendations for the Dyna Rigs design around 2000. Grabe (2002) studied the impact of Dyna Rig on yacht sailing with numerical calculation method. In general, the Dyna Rig can provide 0-100% power to the ship, depending on the wind speed and direction. Nowadays, the Dyna Rig has been widely used on merchant ships, cargo ships, especially on superyachts. The superyacht shown in Figure 2.11 is Maltese Falcon, which is one of the largest sailing yachts in the world. It was built by Perini Navi in Tuzla, Istanbul in 2006, and its Dyna Rigs and masts were designed and built by Magma company. Magna company (2018) introduced that “One unique aspect of the rotating Dyna Rig is that it is possible to utilise the lowest yard as a hoist, which can be used to launch one of the vessel tenders inside two minutes.” Maltese Falcon Mega-Yacht has won many awards from ship owners and the press. This proves that Dyna Rig can be widely installed on board as a highly efficient, safe and practical technology (Magma, 2018).

Figure 2.11 The Maltese Falcon Mega-Yacht under sail (Wilkinson, et al, 2014)

2.5.3 Kite

Kite propulsion is another attractive topic among wind assist technologies. As shown in Figure 2.12, the kite installed on a ship usually flies at altitudes between 100-300 meters from the sea surface where has stronger and more stable winds that can permit the kite to generate almost 25 times the energy efficiency of conventional sails (Alza, 2012). The kite wind propulsion system, also known as Skysails system, usually consists of three main components: A large towing kite with rope, a launch and recovery system, and an electronic control system for automatic operation (SkySails, 2007). In addition to providing much larger energy efficiency, the system is also easy to operate and easy to install. It does not need much space on deck and does not need a ballast condition as the kite only cause very small heel angles (Kindberg, 2015).

Figure 2.12 A ship with towing kite in operation (Fritz, 2013)

As early as in the 1980s, people began the initial research on applying kites to commercial ship propulsion (Wellicome, 1984). Loyd (1980) proposed a model to simulate the flight kite motion and presented examples of large-scale power production to show that the kite efficiency is more comparable to modern wind turbines. Duckworth (1985) studied the application of kites on large ships of the BP fleet and the results have been discussed from both economic and practical considerations. Naaijen, et al (2007, 2010) created a model for calculating the delivered traction force of a kite and discussed the effect of towing force by the kite on both the hull hydromechanics and the existing propulsion installation. George Michael Dadd (2013) presented a method for parameterizing figure of eight shape kite trajectories and for predicting kite velocity and developed a scheme for estimating fuel savings from kite propulsion. Traut, et al (2014) assessed the average power contribution from the Kite ranges from 127 kW to 461 kW and concluded that the transient power is even lower than that from two or more Flettner rotors, but he still admitted the kite is a low carbon technology option. Leloup, et al (2016) presented an optimisation strategy that greatly enhances the propulsive force prediction for a kite and also estimated the fuel saving abilities of a kite on merchant ships with this performance prediction program. In addition to the above, there are also many other scholars who contributed to the research of Kite wind propulsion. Besides, Skysails Company in Germany is one of the most famous companies providing the kite wind propulsion service, who has designed the Skysails system to various ship types (Fritz, 2013). The Wessels Reederei shipping company also makes a great contribution in kite propulsion technology. It was the first shipping company in the world that implemented the kite propulsion system, the Wessels Reederei Company cooperated with Skysails and tested their system on the ship MV Micheal in 2007 and further installed the system on the ship MV Theseus, MV Telamon and MV Peleus after 2009.

2.6 Conclusion

This chapter made a detailed review respectively on ship voyage optimisation, applied algorithms for weather routing, ship routing services and wind assist technologies for shipping. In Section 2.2, the principle of voyage optimisation is summarised, and some relevant research is introduced. The review focused on the speed optimisation. The research situation of speed optimisation methods towards different objectives is reviewed in detail. In Section 2.3, seven classical weather routing algorithms are assessed as the most important part. They are calculus of variations, Isochrone method, Isopone method, Dynamic Programming, Dijkstra’s method, DIRECT method and Evolutionary Algorithms. Every method has its own advantage and disadvantage. Users can select the suitable methods according to shipping requirements and the implementation. In Section 2.4, the state of the art of ship routing services is reviewed comprehensively. It includes not only trans-ocean weather routing services for commercial ships but also services for boat sailing or wins races and small routing apps used in smartphone or tablets. In Section 2.5, three common wind assist technologies including Flettner rotor, Dyna Rig and kite for shipping are reviewed. All the contents provide a good reference for the study in this thesis.

However, some of the limitations of these studies have also been identified as outlined below.

From the perspective of voyage optimisation, most studies did not realise the automatic speed optimisation; Some studies also did not consider ship safety as a strict constraint when calculating the energy efficiency; Most of voyage optimisation methods did not fit well with newly introduced technologies; Many studies did not assign the suitable weight to influences brought by the weather conditions.

From the perspective of weather routing methods, the disadvantages of each method has been clarified. In general, calculus of variations has some complex mathematic principles; Isochrone method are not quite suitable for energy efficiency calculation; The calculation efficiency of Isopone method is not high; The operation of Evolutionary Algorithms is complicated and the optimal solution may not be obtained; For both Dynamic Programming and DIRECT method, the results are extremely sensitive to the variables dimensions; And also the research of DIRECT method is still at the start stage and many details are not considered. Moreover, these methods mainly introduce a large number of assumptions, and some assumptions will affect the most promising results.

From the perspective of routing services, especially for current PC based systems, they are still not scientific enough. Most of the commercial softwares are developed for only coastal routing, and they can only achieve simple objectives, such as avoiding bad weather, ensuring ETA, and choosing the safest route for navigation. Few software can simulate ocean voyages and consider shipping energy efficiency, but still can not reflect the true ship operational performance under various weather condition. Also, they always need to process many data provided by the ship monitor equipment. Besides, these systems are always costly. It is expected that ship managers can develop routing strategies cost effectively through these routing systems.

All the above can also be regarded as the research gap. Therefore, a more advanced weather routing system which reduces these disadvantages as much as possible needs to be developed. The proposed ship weather routing system in this thesis will focus on these limitations and try to make some contribution towards them.

3 Overview of the Methodology for the Weather Routing System

3.1 Introduction

This chapter firstly introduces the requirements for the weather routing system which can be also considered as the goals that the system needs to achieve. After that, the structure of the weather routing system and the workflow between the modules are briefly introduced. The methodology for the weather routing system is generally described from the perspective of each module.

3.2 Requirements for the weather routing system

As mentioned in Section 1.3, this new weather routing system is developed for helping industry and academia understand the intrinsic mechanism of shipping at relative deep level from the perspective of energy saving. This requires the system to have a more comprehensive function and to reflect the characteristics, operating mechanisms and their interactions in the aspects of ship routes, weather condition, ship system, ship response, and energy efficiency and so on accurately and efficiently. Therefore, several requirements are raised for this system:

1. The system must predict the various performances of the ship accurately, including calm water resistance, added resistance due to waves and winds, ship propulsion, ship seakeeping performance etc., and can truly reflect the relationship between the ship performance and the ship system.

2. The system should be able to process the corresponding weather data files automatically and can reflect the relationship between weather factors and ship responses accurately.

3. The system should be able to generate a reasonable grids system automatically to provide guidance for the ship navigation. When encountering some complicated navigational area, the ship should be able to automatically avoid the islands and select relatively reasonable routes.

4. The system should be able to calculate the relationship between ship fuel consumption and ETA correctly. In other words, it can predict the energy efficiency of the ship under different navigation conditions accurately.

5. The system must have an accurate and effective optimisation algorithm that can realise the variable speed functionality for each stage of the route and can calculate the optimal voyage plan based on the ETA given by the user.

6. The system must have the high working efficiency to meet the actual needs of the ship navigation.

7. The system should have intelligent results post-processing function and can extract the entire navigation information of the optimal voyage plan according to the user's needs, including different heading and speed of the ship in different stages, and the weather data and the geographic information of the area that the ship has passed. Finally, the optimal route should be able to be visualised.

8. The system should provide interfaces for other technology modules so that the system can be easily combined with other energy saving devices or technologies introduced. The system has high ductility and can easily calculate the energy efficiency of other devices and technologies.

9. The system should be easy to operate, and its input and output parameters should be concise and easy to understand.

3.3 Methodology for the weather routing system

In order to address all above requirements, the weather routing system is designed to consist of six main modules: ship performance calculation module, ship navigation safety module, grids system design module, weather data module, weather routing module and post-processing module. The only required input parameters are ship particulars and the ship navigation plan which are listed in Table 3.1 while the final output is the optimal voyage plan towards energy efficiency.

Table 3.1 Rquired input parameters of the porposed system

Ship particulars	Ship hull	Ship waterline length; Length between perpendicular; Beam; Depth; Draft; Displacement; Block coefficient; Prismatic coefficient; Midship coefficient; Waterplane area coefficient; Transverse bulb area; Height of the centroid of the transverse bulb area above the base line; Transverse projected area; Longitudinal centre of buoyancy; Stern shape parameter; Mechanical efficiency
	Propeller	Open water test curves
	Engine	Maximum brake power; Specific Fuel Oil Consumption (SFOC) diagram; Ship maximum speed and minimum speed;
	Documents may used	Noon report; Sea trial report; Main engine performance report
Shipping plan	Departure time	
	Estimated time of arrival (ETA)	
	Positions of departure port and destination port	

The structure and workflow of the proposed ship weather routing system are shown in Figure 3.1.

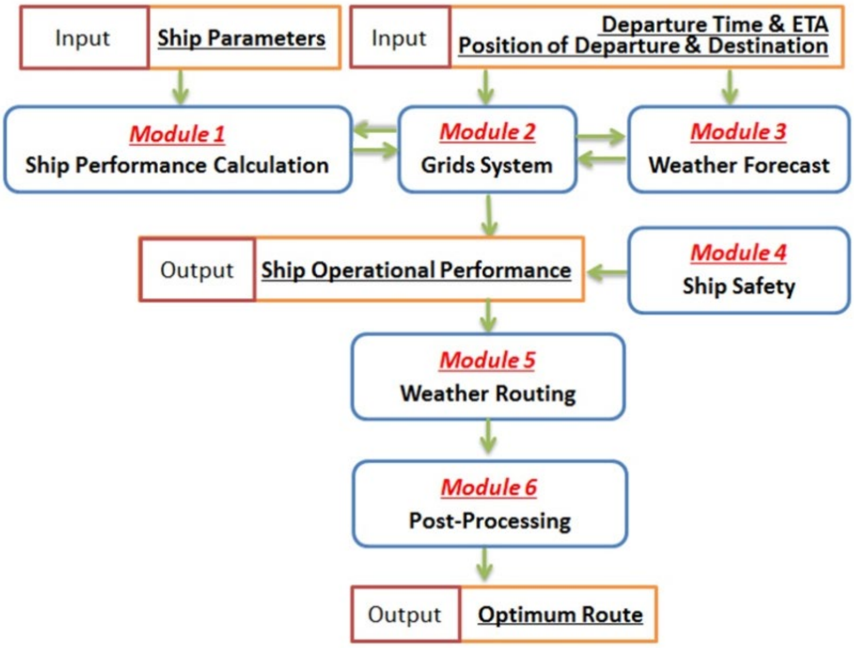


Figure 3.1 Structure and workflow of the weather routing system

After the target ship type is determined, the corresponding ship parameters are fed into the ship performance calculation module. On the other hand, when the shipping plan is set, the geographical space and time ranges are collected according to the sailing time and area, and then they are provided as input into the grids system design module and weather forecast module to establish the grids system and extract weather data of the corresponding time zone required for ship navigation. The data of the grids system design and weather forecast module are transmitted to each other. As the geographic information of a waypoint in the grids system is passed into the weather forecast module to read the weather data, the weather data read from weather forecast module is also sent back to the grids system for ship performance calculation. This also means that the ship performance calculation module and the grids system design module need to communicate with each other. This means, as the weather data needs to be transmitted back to the ship performance calculation module through the grids system for calculation, the calculated ship performance also needs to be sent back to each waypoint in grids system for subsequent other energy-related calculations.

As it can be seen from the above description, the system calculations are concentrated on the waypoint. It not only contains geographic information but also stores all possible sailing times, ship speeds, sailing distances, fuel consumption and even local weather information. In other words, all predicted potential data will be generated in the grids system. These data need to be input into the weather routing module, and ship safety module should be introduced as a constraint to regulate the route of the ship. All the above data is calculated in the weather routing module, and all calculated possible voyage plans are also stored in this module. These results can be processed in the post-processing module to output the final optimal solution which meets user's requirements (ETA or fuel consumption).

The methodology of each module is briefly introduced below.

Module 1: Ship performance calculation

Ship performance calculation is the basis of the whole model, which decides whether the ship voyage plan is very accurate and practically feasible. In this module, the ship performance is judged by the fuel consumption value since the whole system runs towards the energy efficiency. Ship resistance in calm water is estamated based on the Holtrop 1984 method; Ship added resistance due to waves and winds is calculated by the modified Kwon's method and a combined numerical method of Gerritsma & Beukelman's method and Faltinsen's asymptotic method; Based on above results, the brake power can be calculated when the ship propulsion characteristics obtained by the open water test and relevant delivery efficiencies are introduced; Finally, the fuel consumption value can be determined by introducing the main engine parameters.

Module 2: Grids system design module

Designing a grids system to guide the navigation of ships is a common practice in many weather routing studies. This study also uses this method. A parallel distribution of waypoints is adopted to establish the basic grids system, and then the geographical database-GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database) is introduced for the development of the land avoidance function.

Module 3: Weather forecast module

The weather data files including wind files and wave files used in this module is downloaded from ECMWF (European Centre for Medium-Range Weather Forecasts) in the GRIB form. A decoding program is developed to access the GRIB files. So once the position and local time of a waypoint is known, the detailed weather data at that point will be obtained.

Module 4: Ship safety module

This module is established to guarantee the ship navigation safety. NORDFORSK (1987) criteria is introduced as the ship navigation safety criterion in this module. In this criteria, four parameters related to ship seakeeping performance are selected as the ship safety measurements, which are respectively the probability of slamming, the probability of deck wetness, RMS of roll and RMS of vertical acceleration at FP.

Module 5: Weather routing module

This module is the core module of the whole system. It will produce final optimum voyage plans through weather routing optimisation calculation. A combination of global and local optimisation algorithm is developed in this module, and a Pareto front (ETA vs Fuel consumption) will be generated in final destination waypoint, which contains the voyage plan with minimum fuel consumption at any pre-set ETA.

Module 6: Post processing module

The purpose of this module is to help the users do post-processing of the obtained results. The navigation information of the optimal voyage plan can be extracted with a backward iteration algorithm. The resulting route can also be visualised in this module.

3.4 Conclusion

This chapter raised several necessary requirements for the weather routing system and then mainly introduced the structure, the workflow and especially the methodology of the weather routing system from the perspective of each module. Various performance calculation methods and the necessary environmental data required in these modules will be introduced in Chapter 4, and the more detailed working mechanism of each module will be introduced in Chapter 5.

4 Preparatory Knowledge: Ship Performance Calculation and Environmental Data

4.1 Introduction

In the ship weather routing field, people have a consensus that the reliability of the optimal voyage plan derived from the ship weather routing system is based on the following parameters (Shao, 2013):

(i) the accuracy of the estimation of ship response performance in a seaway;

(ii) the quality of environmental data;

(iii) the applicability of ship routing optimisation.

The ship response performance in seaway mainly contains ship resistance in calm water, ship added resistance due to wave and winds, ship propulsion characteristic and even ship seakeeping performance with regards to ship safety. These performances couple with each other and work together on subsequent calculations of ship engine brake power and final fuel consumption.

Environmental data contains weather data and geographical data. Weather data is the most significant factor affecting ship navigation. The ship will adjust its voyage plan including routes and ship speed strategy according to different sea conditions from the view of fuel savings or ship safety. Geographical data can be used to constrain ship routes. It is also helpful for land avoidance function development and makes the optimal result route more practical.

Both ship performance prediction and environmental data are introduced in detail in this chapter. As to the ship routing optimisation, it will be introduced in the following chapters.

4.2 Ship resistance in calm water

Ship resistance in calm water is the basis of the whole brake power calculation flow. There are several theoretical methods for estimating the ship resistance in the calm water. In consideration of smooth operation and without loss of accuracy, the Holtrop 1984 method (Holtrop, 1984) is selected for ship resistance in calm water calculation in this thesis.

Holtrop 1984 method is a statistical regression method based on ship model tests and results from trials. Like many other methods, it decomposes the total calm water resistance into several components, namely:

Resistance decomposition:

$$R_{calm} = (1+k_1)R_F + R_w + R_B + R_{TR} + R_{APP} + R_A \tag{4.1}$$

Where,

R_{calm} : Total resistance.

R_F : Friction resistance from the ITTC 1957 line.

$1+k_1$: Form factor describing the viscous resistance of the hull form in relation to R_F .

R_w : Wave-making and wave-breaking resistance.

R_B : Additional pressure resistance of bulbous bow near the water surface.

R_{TR} : Additional pressure resistance of immersed Transom stern.

R_{APP} : Appendage resistance.

R_A : Model-ship correlation resistance.

There are two ways for implementing Holtrop 1984 method. One way is programming these formulas directly into the weather routing system, while the other way is through the hydrodynamic software. Generally, these hydrodynamic software will contains the basic module of the calm water performance calculation and that usually has Holtrop 1984 method integrated already. Users can call this method very easily as they just need to input the necessary ship particulars and ship speed etc. into the corresponding module. These hydrodynamic software may also supports other calm water resistance calculation methods, like Artificial neural network method, Specify Cr curve method, Hollenbach 98 method, Specify ship resistance (Rt) curve method and CatRes regression analysis method (high-speed displacement catamarans) and so on. Users can select more suitable methods for the calculation of ship clam water performance according to different shipping conditions or situations.

4.3 Ship added resistance

Added resistance is another important component of total ship resistance which is caused by the encountered external environment like wind, wave, current, ice layers and seawater density change and so on. Therefore, it also plays a key role in ship performance calculation which should be considered carefully. In this study, only added resistance due to waves and winds is considered. Because wave and wind are the two most common environmental elements in a seaway and also the added resistance calculation methods for other environmental elements are still not developed maturely. There are many added resistance prediction methods like strip theory based method, far-field method, near-field method and even CFD tools and tank experiment method (Kim, et al, 2017). In this study, an empirical method-modified Kwon's method and a combined numerical method are selected respectively for added resistance prediction.

4.3.1 Kwon's method

Kwon's method (Kwon, 2008) aims to provide a more straightforward and easier way to estimate the effect of wind and waves. When the ship's propulsion power is constant, the added resistance due to waves and wind will cause the ship speed to decrease from the expected speed achieved in calm water. As a data-based method, Kwon's method estimates the effect of added resistance from the view of speed loss. It summaries a set of formulas to estimate the percentage involuntary speed loss under different weather conditions. In this method, the sea condition is described in terms of Beaufort number, Froude number, Direction speed reduction coefficient, Speed reduction coefficient and Ship form coefficient. The main body of this method is introduced as below.

The percentage of speed loss is determined by:

$$\frac{\Delta V}{V_1}100\% = C_\beta C_U C_{Form} \tag{4.6}$$

$$V_1 = F_n\sqrt{L_{pp}g} \tag{4.7}$$

Where,

ΔV : Speed loss due to head weather.

V_1: Design service speed in calm water conditions.

C_β : Direction speed reduction coefficient, dependent on the weather direction angle (with respect to the ship's bow) and the Beaufort number BN as shown in Table 4.1.

C_U : Speed reduction coefficient, dependent on the ship's block coefficient C_B, loading condition and Froude number F_n as shown in Table 4.2.

C_{Form}: Ship form coefficient, dependent on ship types, the Beaufort number BN and ship displacement ∇ as shown in Table 4.3.

F_n: Froude number associated with designed ship service speed V_1 in calm water conditions.

L_{pp} : Ship length between perpendiculars.

g : Gravitational acceleration.

Table 4.1 Direction speed reduction coefficient C_β

Weather direction	Direction angle (with respect to ship's bow)	Direction speed reduction coefficient C_β
Head sea (irregular waves) and wind	0°	$2C_\beta = 2$
Bow sea (irregular waves) and wind	30° to 60°	$2C_\beta = 1.7 - 0.03(BN-4)^2$
Beam sea (irregular waves) and wind	60° to 150°	$2C_\beta = 0.9 - 0.06(BN-6)^2$
Following sea (irregular waves) and wind	150° to 180°	$2C_\beta = 0.4 - 0.03(BN-8)^2$

Table 4.2 Speed reduction coefficient C_U

Block coefficient C_B	Ship loading conditions	Speed reduction coefficient C_U
0.55	normal	$1.7-1.4F_n-7.4(F_n)^2$
0.60	normal	$2.2-2.5F_n-9.7(F_n)^2$
0.65	normal	$2.6-3.7F_n-11.6(F_n)^2$
0.70	normal	$3.1-5.3F_n-12.4(F_n)^2$
0.75	Loaded or normal	$2.4-10.6F_n-9.5(F_n)^2$
0.80	Loaded or normal	$2.6-13.1F_n-15.1(F_n)^2$
0.85	Loaded or normal	$3.1-18.7F_n+28.0(F_n)^2$
0.75	ballast	$2.6-12.5F_n-13.5(F_n)^2$
0.80	ballast	$3.0-16.3F_n-21.6(F_n)^2$
0.85	ballast	$3.4-20.9F_n+31.8(F_n)^2$

Table 4.3 Ship form coefficient C_{Form}

Type of Ship	Ship form coefficient C_{Form}
All ships (except for containerships) in loaded conditions	$0.5BN+BN^{6.5}/(2.7\nabla^{2/3})$
All ships (except for containerships) in ballast conditions	$0.7BN+BN^{6.5}/(2.7\nabla^{2/3})$
Containerships in normal loading conditions	$0.7BN+BN^{6.5}/(22.0\nabla^{2/3})$

4.3.2 Modified Kwon's method

Although the original Kwon's method can simplify the added resistance calculation and has reasonable accuracy under some specific conditions, it still has some limitations. One notable limitation is that the original method was developed based on Series 60 parent hull form which is not a real ship. So the method can be appropriate to hulls similar to this ship type but may not accurately calculate the speed loss of other ship types, especially it may be not appropriate for some latest real ship models. It may produce some errors when applied to some specific ship types. Thus, the original Kwon’s method does not have broad applicability. Therefore, an upgraded method - the modified Kwon’s method proposed by Strathclyde University (Lu, 2016) as part of Shipping in Changing Climate (SCC) project is utilised in this thesis. The modified Kwon’s method is ship type specific so that it can provide a more accurate prediction for the added resistance performance of a particular ship type.

It was suggested within SCC project that more accurate formulas should be introduced when using Kwon's method to estimate the ship speed loss. Compared with original Kwon's method, the Modified Kwon's method will improve the coefficients of the formula towards the parameters of C_β and C_{Form} according to a complex calculation process. The detailed process is introduced as below.

A precondition should be set in the first place: The modified Kwon’s method is proposed under the assumption that all coefficients have the same equation form including variables as the original Kwon’s method. The estimated formula of the ship form coefficient (C_{Form}) is formulated as the equation given below including two undefined constants (a_1 and a_2)

$$C_{Form} = a_1 \cdot BN + a_2 \cdot \frac{BN^{6.5}}{\nabla^{2/3}} \tag{4.8}$$

As the same way of the ship form coefficient (C_{Form}), the estimated formula of the speed reduction coefficient (C_β) is determined using the equation below including two undefined constants (b_1 and b_2)

$$C_\beta = b_1 - b_2 (BN - 4 \text{ or } 6 \text{ or } 8)^2 \tag{4.9}$$

So the problem becomes how to determine these undefined constants. Based on the above assumptions, three steps are taken to calculate the undefined constants.

Firstly, an index is introduced to make a comparison between the predicted ship performance using original Kwon’s method and the actual recorded ship performance on board. It may be “Energy Efficiency of Operation” (EEO) or ship main engine “Fuel Consumption Rate” (FCR). Both of them are introduced as below.

“Energy Efficiency of Operation” (EEO) is a monitoring index for measuring the fuel efficiency of a ship in operation over time, which can be defined as:

$$EEO = \frac{FC}{m_{cargo} \times Distance} \tag{4.10}$$

Where,

FC : Main engine fuel consumption.

m_{cargo} : Mass of cargo carried on board.

$Distance$: Distance corresponding to the cargo carried.

“Fuel Consumption Rate” (FCR) is also the main index to measure the fuel economy and efficiency of the ship main engine. which can be defined as:

$$FCR = P_B \cdot sfoc \tag{4.11}$$

Where,

$sfoc$: Specific fuel oil consumption, which means the amount of fuel consumed in unit time for generating per kW of power in an engine.

Table 4.4 Example of the data structure in noon report

Operating date	Achieved speed	Position	Mean draft
00/00/0000	12.3 knots	44°30'W\ 12°35'N	11.7 m
B.N. (strongest)	B.N. (average)	Wind direction*	FOC(HFO)
5	4	A	32.3 ton

*Note: A (head sea), B and H (bow sea), C and G (beam sea), and D, E, F (following sea)

Both of the above indexes can be easily obtained by the data recorded in ship noon report as shown in Table 4.4. In this step, the fouling effect can also be considered to make the final method more accurate.

Secondly, based on the comparison results and the premise (4.8) and (4.9), the formulas towards C_{Form} and C_β will be modified, and the regression method will be used to determine the undefined constants a_1, a_2, b_1 and b_2 which make the predicted ship performance index generate from new formulas more closed to the actually recorded index. Here, several other methods can be also applied for the coefficients confirmation and several coefficient results combination may be obtained. The coefficients providing minimum error between the recorded index and predicted index will be selected for the final speed loss prediction formulas for a specific ship type.

Thirdly, the newly developed method will be applied to another same type ship for verification by comparing its predicted ship performance with its recorded ship performance. If the improvement in prediction accuracy meets the requirement, this modified Kwon's method will be regarded as the reasonable speed loss prediction method for this specific ship type.

Since different ships will have different performance in a seaway, therefore, a specialised modified Kwon's method can be developed for every certain ship type. Take a 115K DWT Crude Oil Tanker (COT) as an example, its corresponding Kwon's method after modification is shown in Table 4.5 and Table 4.6. The original Kwon's method is also listed for the aim of comparison.

Table 4.5 Direction speed reduction coefficient C_β of an oil tanker

Direction angle (deg.)	C_β (Kwon's method)	C_β (modified Kwon's method)
Head sea (0°)	$2C_\beta = 2$	$2C_\beta = 3$
Bow sea (30° - 60°)	$2C_\beta = 1.7 - 0.03(BN-4)^2$	$2C_\beta = 2.3 - 0.03(BN-4)^2$
Beam sea (60° - 150°)	$2C_\beta = 0.9 - 0.06(BN-6)^2$	$2C_\beta = 1.1 - 0.06(BN-6)^2$
Following sea (180°)	$2C_\beta = 0.4 - 0.03(BN-8)^2$	$2C_\beta = 0.8 - 0.03(BN-8)^2$

Table 4.6 Ship form coefficient C_{Form} of an oil tanker

Ship type and loading condition	C_{Form} (Kwon's method)	C_{Form} (modified Kwon's method)
Oil tanker in laden condition	$C_{Form} = 0.5BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$	$C_{Form} = 0.6BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$
Oil tanker in ballast condition	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$

Similarly, the modified Kwon's method for a Container Ship is shown in Table 4.7 and Table 4.8.

Table 4.7 Direction speed reduction coefficient C_β of a container ship

Direction angle (deg.)	C_β (Kwon's method)	C_β (modified Kwon's method)
Head sea (0°)	$2C_\beta = 2$	$2C_\beta = 3$
Bow sea (30° - 60°)	$2C_\beta = 1.7 - 0.03(BN-4)^2$	$2C_\beta = 2.3 - 0.03(BN-4)^2$
Beam sea (60° - 150°)	$2C_\beta = 0.9 - 0.06(BN-6)^2$	$2C_\beta = 1.5 - 0.06(BN-6)^2$
Following sea (180°)	$2C_\beta = 0.4 - 0.03(BN-8)^2$	$2C_\beta = 0.8 - 0.03(BN-8)^2$

Table 4.8 Ship form coefficient C_{Form} of a container ship

Ship type and loading condition	C_{Form} (Kwon's method)	C_{Form} (modified Kwon's method)
Container Ship in normal condition	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{22\nabla^{2/3}}$	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{22\nabla^{2/3}}$

In the same way, take a Bulk Carrier with 35,500DWT and 175.72 meters length as an example, its corresponding modified Kwon's method is shown in Table 4.9 and Table 4.10.

Table 4.9 Direction speed reduction coefficient C_β of a bulk carrier

Direction angle (deg.)	C_β (Kwon's method)	C_β (modified Kwon's method)
Head sea (0°)	$2C_\beta = 2$	$2C_\beta = 3$
Bow sea (30° - 60°)	$2C_\beta = 1.7 - 0.03(BN-4)^2$	$2C_\beta = 2.3 - 0.03(BN-4)^2$
Beam sea (60° - 150°)	$2C_\beta = 0.9 - 0.06(BN-6)^2$	$2C_\beta = 1.5 - 0.06(BN-6)^2$
Following sea (180°)	$2C_\beta = 0.4 - 0.03(BN-8)^2$	$2C_\beta = 0.8 - 0.03(BN-8)^2$

Table 4.10 Ship form coefficient C_{Form} of a bulk carrier

Ship type and loading condition	C_{Form} (Kwon's method)	C_{Form} (modified Kwon's method)
Bulk carrier ship in loaded conditions	$C_{Form} = 0.5BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$	$C_{Form} = 0.6BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$
Bulk carrier ship in ballast conditions	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$	$C_{Form} = 0.7BN + \frac{BN^{6.5}}{2.7\nabla^{2/3}}$

The modified Kwon's method is easy to be programmed in the weather routing system, and it is regarded this method can provide the reasonable accuracy of the final ship performance results. However, it is worth noting that whether Kwon's method or Modified Kwon's method is unlikely to be accurate for Beaufort numbers above six although these extreme cases will not occur in most sea routes. This is why the proposed weather routing model has additional added resistance prediction model to cover the sea states above BN 6 as well as the sea states below BN6.

4.3.3 Combined numerical method

Gerritsma & Beukelman's method (1972) is a far-field method based on the momentum conservation theory (Kim et al, 2017). Loukakis and Sclavounos (1978) extended this method from only valid for head sea waves to oblique waves.

The basic idea of this method is that the added resistance of a ship advancing in waves can be regarded as equivalent to the energy contained in the damping waves radiated away from the ship. The damping wave is caused by the vessel oscillating in the vertical plane and radiating energy from the hull. This energy can act on the seawater and then create waves that can radiate to infinity. Since this method predicts the ship added resistance from the view of radiated energy and it is also a so-called radiated energy method (Arribas, 2007; Zakaria, et al, 2007; Alexandersson, 2009; Stamatis, 2013). This method has been widely used in ship hydromechanics. Its main added resistance calculation formula is expressed as:

$$R_{aw} = \frac{-k \cdot \cos(\beta)}{2 \cdot \omega_e} \int_0^L b' \cdot \left| V_{Z_b} \right|^2 \cdot \partial x_b \tag{4.12}$$

Where,

k : Wave number.

β : Heading angle.

ω_e : Wave encounter frequency.

L : Water line length of the ship.

$\left| V_{Z_b} \right|$: The amplitude of the velocity of water relative to the strip.

b' : The sectional damping coefficient for speed.

x_b : The x coordinate on the ship.

The relationship between radiated energy during one period of oscillation and added resistance can be expressed as:

$$E = R_{aw} \cdot \lambda_\beta \tag{4.13}$$

Where, λ_β is the wave length that the ship experiences when it is heading diagonally through the waves.

However, the Gerritsma & Beukelman's method always performs very poor in the prediction of the added resistance for following seas especially when the ship speed is relatively high. Because this method is developed based on strip theory which sets an assumption of low Froude number, high frequency and slender body for added resistance calculation (McTaggart, et al, 1997). For some cases where encounter frequency is low and ship speed is high, the radiation forces cannot be predicted accurately and this will lead to wrong results.

Therefore, another method Faltinsen's asymptotic method (Faltinsen, et al, 1980, 1990) is also introduced to calculate the added resistance of ships in short waves. This is a near-field method, assuming that the vessel has vertical sides at the water plane and that the incident wavelength is small compared to the draught of the vessel. The drift force is then obtained by the direct pressure integration along the surface of the hull where the drift forces are dominated by the relative motion of the ship. This method also takes into account an approximation of the interaction of diffraction waves with steady current around the hull (Guo, et al, 2011; Martin Alexandersson, 2009; Kim et al, 2017; Yang, 2018).

The added resistance with Faltinsen's asymptotic method can be calculated by the following formula:

$$R_{aw} = \frac{\rho \cdot g}{2} \cdot \zeta_a^2 \left(1 + \frac{2 \cdot \omega \cdot U}{g}\right) \cdot \int_{L_1} \sin(\theta + \beta) \cdot n_x \cdot \partial l \tag{4.14}$$

Where,

ρ: The water density.

g: Gravitational acceleration.

ζ_a: Wave amplitude.

ω: Wave frequency.

L_1: The non-shadow length of the waterline.

β: Heading angle.

n_x: x component of the normal vector of the hull.

The mean added resistance (ΔR_{wave}) can also be non-dimensionalised as follow:

$$\sigma_{aw} = \frac{\Delta R_{wave}}{\rho g \zeta^2 B^2 / L} \tag{4.15}$$

Where,

ζ : The wave amplitude parameters.

B : Ship breath.

Besides, the added resistance due to winds (ΔR_{wind}) can be predicted by the following formula (IMO, 2012):

$$\Delta R_{wind} = \frac{1}{2} \rho_{air} A_T C_D \left\{ (U_{wind} + V_w)^2 - V_{ref}^2 \right\} \tag{4.16}$$

Where,

ρ_{air} : The air density.

A_T : The frontal projected transverse area above the designated load condition.

U_{wind} : Mean wind speed.

V_w: Design ship speed when the ship is in operation under the representative sea condition.

V_{ref} : Design ship speed when the ship is in operation in a calm sea condition (no wind and no waves).

C_D : Drag coefficient due to the wind, which can be obtained from the wind loading chart (Blendermann, 1994) based on wind tunnel tests of ship models or directly from the empirical formula as below:

$$C_D = 0.922 - 0.507 \frac{A_L}{L_{OA} B} - 1.162 \frac{C}{L_{OA}} \tag{4.17}$$

Where,

A_L: Projected lateral area above the designated load condition.

B : Ship breath.

C : Distance from the midship section to the centre of the projected lateral area (A_L); a positive value of C means that the centre of the projected lateral area is located ahead of the midship section.

L_{OA} : Ship length overall.

Based on above, in order to obtain more accurate ship added resistance performance, a combined method of Gerritsma & Beukelman's method and Faltinsen's asymptotic method can be applied in ship weather routing system, so that users can make use of both two methods' advantages (far-field method and near-field method). This process can be also realised in hydrodynamic software for the sake of easy operation.

4.4 Ship propulsion

Ship propulsion performance is also the essential prerequisite for the calculation of the brake power and even fuel consumption. The propeller characteristics are always obtained by the open water test. The definition of key parameters of ship propulsion and the calculation of final brake power are briefly introduced as below.

A propeller operating in open water can be characterised by two non-dimensional parameters:

Thrust Coefficient:

$$K_T = \frac{T}{\rho n^2 D^4} \tag{4.18}$$

Where,

T : Propeller Thrust;

ρ : Density of water;

n : Propeller rotation speed;

D : Diameter of the propeller.

And the torque coefficient:

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{4.19}$$

Where,

Q: Propeller torque in open water.

Thrust coefficient and torque coefficient are often given as a function of the advance ratio, which is defined as:

$$J = \frac{V_A}{nD} \tag{4.20}$$

Where,

V_A: Propeller's speed of advance.

A typical open water test curves with thrust and torque coefficients, advance ratio and open water efficiency of an example propeller is shown in Figure 4.1.

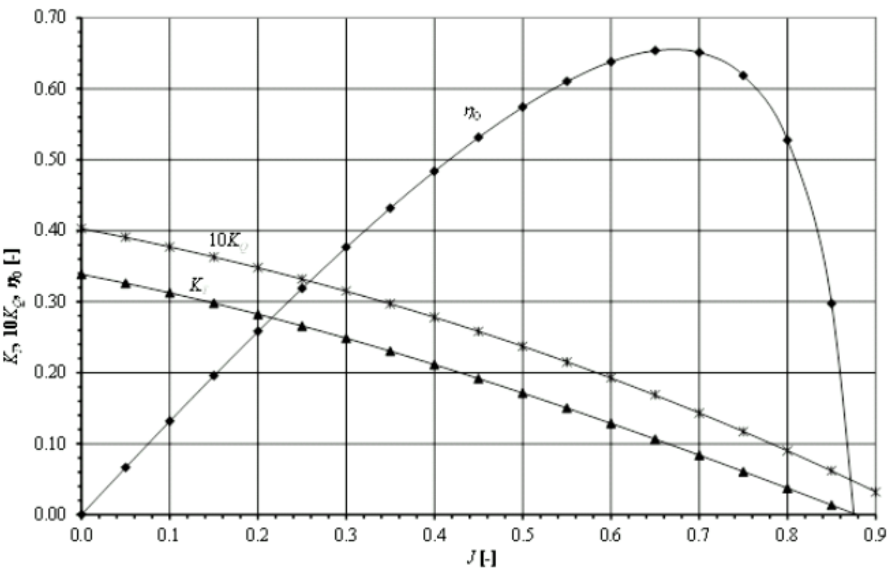


Figure 4.1 Open water test curves of an example propeller (Model Propeller: VP1304)

The K_T / J^2 value can be determined as:

$$\frac{K_T}{J^2} = \frac{T}{\rho V_A^2 D^2} = \frac{R}{\rho (1-\tau)(1-\omega)^2 V^2 D^2} \tag{4.21}$$

Thrust deduction and wake fraction are two indirect expressions of the interaction between the hull and the propeller.

Thrust deduction:

$$\tau = \frac{T - R}{T} \tag{4.22}$$

Where,

R : Ship resistance.

Wake fraction:

$$\omega = \frac{V - V_A}{V} \tag{4.23}$$

V : Ship speed.

Since the K_T vs J curve shown in Figure 4.1 is obtained by propeller open water test, another K_T / J^2 vs J curve can be also derived based on this curve. So when the value of K_T / J^2 is determined by formula 4.21, the advance ratio J can be also determined by interpolation in K_T / J^2 vs J curve. With the known advance ratio J, the propeller rotation speed n can be finally calculated by formula 4.20.

Besides, three very important delivery efficiencies are calculated as below.

Open water efficiency:

$$\eta_0 = \frac{TV_A}{2\pi nQ} \tag{4.24}$$

Which can be also defined based on the above formulas as:

$$\eta_0 = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \tag{4.25}$$

Hull efficiency:

$$\eta_H = \frac{1 - t}{1 - \omega} \tag{4.26}$$

Rotative efficiency:

$$\eta_R = \frac{Q_0}{Q} \tag{4.27}$$

Finally, based on all above, the engine brake power can be calculated as:

$$P_B = \frac{P_E}{\eta_T} \tag{4.28}$$

Where, P_E is the effective power, which can be calculated as:

$$P_E = R_T \cdot V \tag{4.29}$$

and η_T is the total efficiency, which can be calculated as:

$$\eta_T = \eta_0 \cdot \eta_H \cdot \eta_R \cdot \eta_M \tag{4.30}$$

Where, R_T is the ship total resistance and η_M is the mechanical efficiency.

In this study, all the above calculation can be also completed in inhouse/commercial hydrodynamic software, since some software has collected many typical propeller models and their open water test results and diagrams. When a specific propeller is determined, the hydrodynamic software will produce the propulsion characteristic and the relevant value of total delivery efficiencies under different travel conditions, and then the brake power can be easily calculated. Finally, the value of brake power will be passed to the ship weather routing system for the calculation of the fuel consumption which is elaborated in Section 5.2.1. In addition to the hydrodynamic software, all the above formulas can be also programmed directly into the ship weather routing system for simple ship propulsion performance simulation.

4.5 Ship safety

The ship navigation safety not only means the ship hull safety but also includes the crew safety, cargo safety and even equipment safety on the ship. It usually relates to the ship's seakeeping performance. Here, hydroelasticity or ship structural limits bending moments and shear forces are not taken into account. Over the last few decades, many standards or criteria have been proposed to guarantee the ship safety and regulate its operability limits. Most common criteria (Ghaemi, et al, 2017) are:

i. Motion Induced Interruptions (MII), Baitis (1995);

ii. Motion Sickness Incidence (MSI), O'Hanlon and McCauly (1974);

iii. The North Atlantic Treaty Organisation Standard Agreement 4154 (NATO STANAG 4154);

iv. U.S. Navy and U.S. Coast Guard Cutter Certification Plan;

v. NORDFORSK (1987);

vi. ISO 2361/3-1985 (in relation to vertical acceleration);

vii. IMO Revised Guidance to the masters for Avoiding Dangerous Situations in Adverse Weather and Sea Conditions (2007).

Generally, all the above criteria mainly focus on ten seakeeping performance items. They are:

1. Slamming;
2. Deck wetness;
3. Accelerations;
4. Roll;
5. Pitch;
6. Heave;
7. Displacement;
8. Local relative motion;
9. Propeller emergence;
10. Broaching.

In consideration of easy to understand and operate, NORDFORSK (1987) is selected as the ship navigation criterion to guarantee the ship safety in this study. The General operability limiting criteria for ships are shown in Table 4.11.

Table 4.11 General operability limiting criteria for ships (NORDFORSK, 1987)

Description	Merchant Ships	Navy Vessels	Fast Small Craft
RMS of vertical acceleration at FP	0.275g (L≤100m) 0.050g (L≥330m)*	0.275g	0.65g
RMS of vertical acceleration at Bridge	0.15g	0.20g	0.275g
RMS of lateral acceleration at Bridge	0.12g	0.10g	0.10g
RMS of Roll	6.0deg	4.0deg	4.0deg
Probability of Slamming	0.03 (L≤100m) 0.01 (L≥330m)*	0.03	0.03
Probability of Deck Wetness	0.05	0.05	0.05

*The limiting criterion of both RMS of vertical acceleration at FP and Probability of Slamming for lengths between 100 and 300 m varies linearly between the values L = 100 m and L = 300 m. (Faltinsen, 2005)

Four seakeeping items: the probability of slamming, the probability of deck wetness, RMS of roll and RMS of vertical acceleration at FP are calculated as measurements to estimate the ship safety (Eskild, 2014). The calculation of these parameters is briefly introduced as follows.

Wave spectrum is the first important effect factor for seakeeping performance calculation. When concerning the ship response in waves, people always use the wave spectrum, also known as its full name wave amplitude energy density spectrum, to mathematically describe the distribution of wave energy with wave frequency and direction for given sea conditions.

The JONSWAP (Joint North Sea Wave Project) spectrum is one of the typical wave spectrums, which has been used widely in different research scenarios. Here, the JONSWAP spectrum is introduced as an example to explain how to calculate the relevant ship safety performance.

According to DNV Classification Notes 30.5 (Veritas, 1991), the spectral density function for the JONSWAP spectrum can be written as:

$$S(\omega) = \alpha g^2 \omega^{-5} e^{-\frac{5}{4}(\frac{\omega_p}{\omega})^4} \gamma^{e^{-\frac{1}{2}(\frac{\omega-\omega_p}{\sigma\omega_p})^2}} \tag{4.31}$$

Where,

α : Spectral parameter.

g : Acceleration of gravity.

ω : Wave frequency.

ω_p : Peak frequency.

γ : Peakedness parameter.

σ : Spectral width parameter, $\sigma = 0.07$ for $\omega < \omega_p$ and $\sigma = 0.09$ for $\omega > \omega_p$.

Transfer functions are another important effect factors to estimate the seakeeping performance. The transfer function, which can be also regarded as response amplitude operator (RAO), is a mathematical function to determine the effect that a sea state will have upon the motion of a ship through the water. They are usually obtained from models of proposed ship designs tested in a model basin or from running specialised CFD computer programs, often both. They are usually calculated for all ship motions and all wave headings. The transfer function for the corresponding degree of freedom is defined as:

$$H_j(\omega) = \frac{\eta_j(\omega)}{\varsigma_a} \tag{4.32}$$

Where,

$\eta_j(\omega)$: Response functions.

ς_a : Wave amplitude.

Through combining wave spectrum with the transfer function, the response of the vessel in the irregular sea can be defined as:

The relative vertical motion:

$$\sigma_r^2 = \int_0^\infty S(\omega)\left|H_r(\omega)\right|^2 d\omega \tag{4.33}$$

The relative vertical velocity:

$$\sigma_v^2 = \int_0^\infty \omega^2 S(\omega)\left|H_v(\omega)\right|^2 d\omega \tag{4.34}$$

The relative vertical acceleration (The RMS vertical acceleration at the FP was computed at a point located on the main deck and on the centreline.):

$$\sigma_{va}^2 = \int_0^\infty \omega^4 S(\omega)\left|H_{va}(\omega)\right|^2 d\omega \tag{4.35}$$

The standard deviation for roll:

$$\sigma_{roll}^2 = \int_0^\infty S(\omega)\left|H_{roll}(\omega)\right|^2 d\omega \tag{4.36}$$

The probability of slamming:

$$P(\text{slamming}) = e^{-\left(\frac{V_{cr}^2}{2\sigma_v^2}+\frac{T^2}{2\sigma_r^2}\right)} \tag{4.37}$$

The probability of deck wetness:

$$P(\text{deck wetness}) = e^{-\frac{F^2}{2\sigma_r^2}} \tag{4.38}$$

Where,

$H_r(\omega)$: Transfer function for relative vertical motion.

$H_v(\omega)$: Transfer function for the relative velocity.

$H_{va}(\omega)$: Transfer function for the relative vertical acceleration.

$H_{roll}(\omega)$: Transfer function for roll.

F : Freeboard.

T : Draft.

V_{cr} : Threshold velocity, $V_{cr} = 0.093\sqrt{gL}$.

L : Length.

All of the above parameters can also be easily calculated in some hydrodynamic software, which will calculate different transfer functions and further response results. If without hydrodynamic software, all the formulas can also be programmed in to weather routing system for seakeeping performance calculation. The ship navigation safety can be guaranteed when these items meet their corresponding criteria, which are explained in chapter 5.

4.6 Environmental data

As previously mentioned, the quality of environmental data plays an essential role in the reliability of the optimal route derived from the ship weather routing system. In this section two critical environmental data: weather data and geographical data are introduced in detail.

4.6.1 Weather data

The weather data used in this study is downloaded from ECMWF (European Centre for Medium-Range Weather Forecasts) in the GRIB form.

ECMWF (accessed 2014), which is established in 1975, is an independent intergovernmental research institute supported by 34 states. The Centre has one of the largest supercomputer facilities and associated meteorological data archives in the world. It provides weather services including producing global numerical weather forecasts for the users worldwide.

GRIB (GRIdded Binary or General Regularly-distributed Information in Binary form) is a concise file format for the storage and transport of gridded historical and forecast meteorological data. It is defined, standardised and maintained by the World Meteorological Organisation's Commission for Basic Systems from 1985. GRIB files are a collection of self-contained records of 2D data, arranged as a sequential bit stream. Each record begins with a header, followed by packed binary data (GRIB, accessed 2014). GRIB's major advantages are files are typically 1/2 to 1/3 of the size of normal binary files (floats) and GRIB is an open, international standard. Another advantage of GRIB is that is self-describing. Each record has information such as: resolution of the grid, time, variable, level and who created the field. Users should use special programmes to create, decode and even display the GRIB file.

In this study, the most concerned weathers are wind data and wave data. Both of these two weather files are downloaded with the time interval of every six hours a day and $0.75° \times 0.75°$ resolution of grids. The wind GRIB file contains the following attributes:

1. 2 meter dewpoint temperature;

2. 2 meter temperature;

3. 10 meter U wind component;

4. 10 meter V wind component;

5. High cloud cover;

6. Ice temperature layer 1;

7. Low cloud cover;

8. Mean sea level pressure;

9. Medium cloud cover;

10. Sea surface temperature;

11. Sea-ice cover;

12. Skin temperature;

13. Snow density;

14. Surface pressure;

15. Surface roughness;

16. Total cloud cover.

Besides, according to the attributes of 10 meter U wind component and 10 meter V wind component in wind GRIB file, the wind speed can be converted to corresponding Beaufort Number when calculating the added resistance with modified Kwon's method. The Beaufort wind scale is shown in Table 4.12.

Table 4.12 Beaufort wind scale

Beaufort No. (B.N.)	Name	Wind speed (m/s)	Wave height (m)	Hs_{max} (m)
0	Calm	0.0 ~ 0.2	0.0	0.0
1	Light air	0.3 ~ 1.5	0.0 ~ 0.2	0.2
2	Light breeze	1.6 ~ 3.3	0.2 ~ 0.5	0.5
3	Gentle breeze	3.4 ~ 5.4	0.5 ~ 1.0	1.0
4	Moderate breeze	5.5 ~ 7.9	1.0 ~ 2.0	2.0
5	Fresh breeze	8.0 ~ 10.7	2.0 ~ 3.0	3.0
6	Strong breeze	10.8 ~ 13.8	3.0 ~ 4.0	4.0
7	High wind, moderate gale, near gale	13.9 ~ 17.1	4.0 ~ 5.5	5.5
8	Gale, fresh gale	17.2 ~ 20.7	5.5 ~ 7.5	7.5
9	Strong/severe gale	20.8 ~ 24.4	7 ~ 10	10
10	Storm, whole gale	24.5 ~ 28.4	9 ~ 12.5	12.5
11	Violent storm	28.5 ~ 32.6	11.5 ~ 16	16
12	Hurricane force	≥32.7	≥14	16

The wave GRIB file contains the following attributes:

1. Mean wave direction;

2. Mean wave period;

3. Significant height of combined wind, waves and swell.

All these weather data files contain time, latitude and longitude. So once local time, latitude and longitude at a certain point on the earth are given, detailed weather data at that point will be known through the decoding operation. In this research, 36 years (1979-2014) global historical weather data is downloaded for the shipping simulation.

4.6.2 Geographical data

To constrain the shipping route from the geographic perspective and to make the optimal route more accurate and practical, a geographical database-GSHHG (Global Self-consistent, Hierarchical, High-resolution Geography Database) is introduced to the ship weather routing system. GSHHG is a high-resolution shoreline data set which draws the outline of the entire world and shows very clear bound between land and water areas. The data in GSHHG have undergone extensive processing and are free of internal inconsistencies such as erratic points and crossing segments. The shorelines are constructed entirely from hierarchically arranged closed polygons. The world map drawn by the GSHHG database is shown in Figure 4.2.

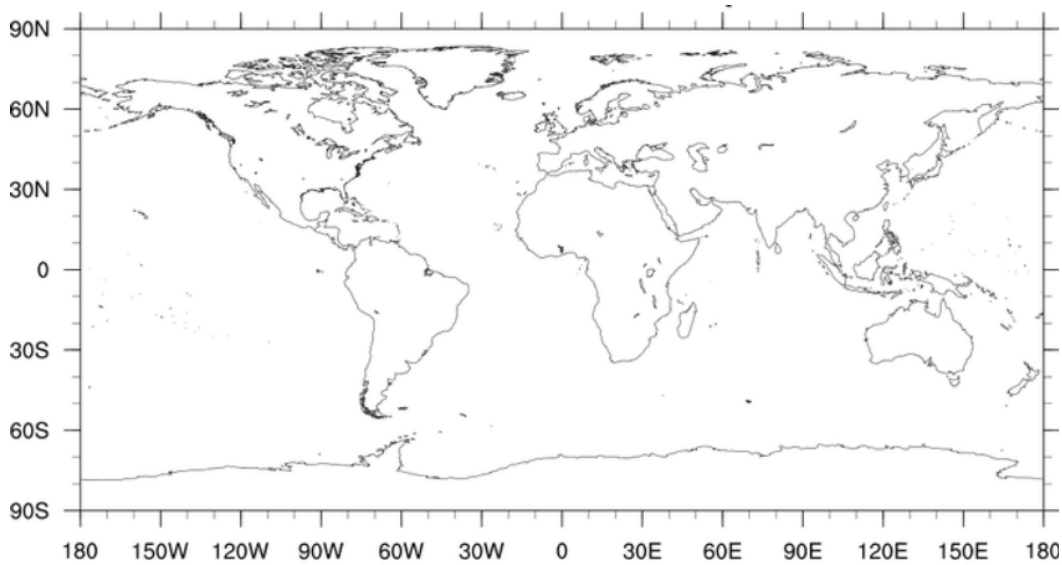


Figure 4.2 Outline of the world from GSHHG (©UCAR 2018. [www.ncl.ucar.edu/Applications/Images/mapoutlines_5_3_lg.png] Last accessed October 2016)

GSHHG provides comprehensive and detailed data levels so that users can select the corresponding level according to their own requirements.

In GSHHG, the geography data come in five resolutions:

1. Full resolution: Original (full) data resolution;

2. High resolution: About 80 % reduction in size and quality;

3. Intermediate resolution: Another ~80 % reduction;

4. Low resolution: Another ~80 % reduction;

5. Crude resolution: Another ~80 % reduction.

Unlike the shoreline polygons at all resolutions, the lower resolution rivers are not guaranteed to be free of intersections.

Shorelines are furthermore organised into 6 hierarchical levels:

1. L1: boundary between land and ocean, except Antarctica;

2. L2: boundary between lake and land;

3. L3: boundary between island-in-lake and lake;

4. L4: boundary between pond-in-island and island;

5. L5: boundary between Antarctica ice and ocean;

6. L6: boundary between Antarctica grounding-line and ocean.

Rivers are organised into 10 classification levels:

1. L0: Double-lined rivers (river-lakes);

2. L1: Permanent major rivers;

3. L2: Additional major rivers;

4. L3: Additional rivers;

5. L4: Minor rivers;

6. L5: Intermittent rivers - major;

7. L6: Intermittent rivers – additional;

8. L7: Intermittent rivers – minor;

9. L8: Major canals;

10. L9: Minor canals;

11. L10: Irrigation canals;

Finally, borders are organised into three levels:

1. L1: National boundaries;

2. L2: State boundaries within the Americas;

3. L3: Marine boundaries.

GSHHG is developed and maintained by the University of Hawai'I and NOAA Laboratory for Satellite Altimetry. So this database can be downloaded from the University of Hawai'I website (accessed 2014) or the NOAA (National Oceanic and Atmospheric Administration) website (accessed 2014). The more detailed introduction of GSHHG can be found in the document published by Wessel, et al (1996). GSHHG is integrated into the ship weather routing system for its land avoidance function development.

4.7 Conclusion

This chapter introduced the preparatory knowledge in detail which will be used for the development of ship weather routing system. The first part is aimed to introduce some basic calculation principles and methods of concerned ship performance. They are respectively: ship resistance in calm water, ship added resistance due to waves and winds, ship propulsion and ship safety. Among them, ship resistance in calm water is predicted by Holtrop 1984 method; Ship added resistance is estimated by modified Kwon’s method or a combined numerical method of Gerritsma & Beukelman’s method and Faltinsen’s asymptotic method; while the NORDFORSK (1987) criteria regarded to ship seakeeping performance is selected for the guarantee of ship safety. Almost all the calculation can be implemented in the hydrodynamic software and of course, they can be also programmed to the weather routing system directly. Users can select most reliable and easiest way to perform the weather routing calculation depending on the availability of various tools. The second part is aimed to introduce the environmental data which contains weather data and geographical data. Both parts will also have a huge impact on the reliability of the final voyage plan. The detailed usage of these methods and environmental data will be introduced in Chapter 5.

5 Ship Weather Routing System

5.1 Introduction

This chapter introduces the core content of this study: the ship weather routing system. This system is developed towards energy efficiency shipping and has related comprehensive functions. It contains several necessary modules: ship performance calculation module, ship navigation safety module, grids system design module, weather data module, weather routing module and post-processing module. The role of each module and the relationship between the modules are introduced in detail. The input and output of the entire system are also clearly explained. At last, a typical case study is considered to verify the validity of the system preliminarily.

5.2 Ship weather routing system

The structure and workflow of the proposed ship weather routing system has been described in Section 3.3. Next, each specific module is introduced in detail as below.

5.2.1 Ship performance calculation module

In this module, the ship performance refers to the engine brake power and then the final fuel consumption. The calculation process of ship performance involves a number of calculations such as the ship's calm water resistance, ship added resistance and ship propulsion. The calculation methods for these attributes have been elaborated in Chapter 4. They can be directly calculated by programming the formula in the system, and can also be calculated by the hydrodynamic software, and then the result can be obtained through data post-processing. The following describes the calculation flow for the final ship performance: fuel consumption.

1. The entire calculation flow starts at the ship speed in calm water. Suppose the ship is sailing in the ocean at a certain calm water speed. Since the calm water speed of the ship is known, combined with the particulars of the ship, it is possible to evaluate the ship calm water resistance based on Holtrop 1984 method.

2. The weather data of wind and waves is introduced according to the ship's travel time and shipping area so that the ship added resistance due to waves and winds can

be estimated and then ship speed loss is also calculated. This step is realised by either modified Kwon's method or the combined numerical method.

3. Combining the calm water speed of the ship with the calculated ship speed loss, the true speed of the ship sailing in the ocean can be calculated.

4. The ship calm water resistance (R_{calm}) and added resistance due to waves (ΔR_{waves}) and winds (ΔR_{winds}) constitute the total resistance of the ship (R_T), which can be explained by

$$R_T = R_{calm} + \Delta R_{waves} + \Delta R_{winds} \tag{5.1}$$

5. The effective power of the ship's main engine (P_E) can be calculated from the total resistance of the ship (R_T) and the true speed of the ship (V_{ship}). Thus,

$$P_E = R_T \cdot V_{ship} \tag{5.2}$$

6. Based on the known effective power (P_E), together with the introduced propeller open water performance and other power transfer efficiency, the ship brake power P_B can be calculated by

$$P_B = \frac{P_E}{\eta_0 \cdot \eta_H \cdot \eta_R \cdot \eta_M} \tag{5.3}$$

Detailed calculation of this step has been introduced in Section 4.4.

7. Finally, the fuel consumption for a certain route can be calculated by:

$$FC = P_B \cdot sfoc \cdot t \tag{5.4}$$

Where, t is ship navigation duration, which can be easily obtained when the length of the route and the true ship speed are known. $sfoc$ (g/kWh) is specific fuel oil consumption of the engine.

Specific fuel oil consumption (SFOC) changes with the engine loading. A SFOC vs Engine load curve of example engine (Model engine: MAN B&W 7S60MC6.1-TII) is shown in Figure 5.1. Engine load is related to RPM, so when RPM is calculated in Section 4.4, the corresponding engine load will be determined through main engine performance diagram as well, or the engine load can be calculated as a portion of utilized engine power. Finally, when engine load is determined, the utilised SFOC value for fuel consumption calculation is confirmed by the SFOC vs Engine load curve.

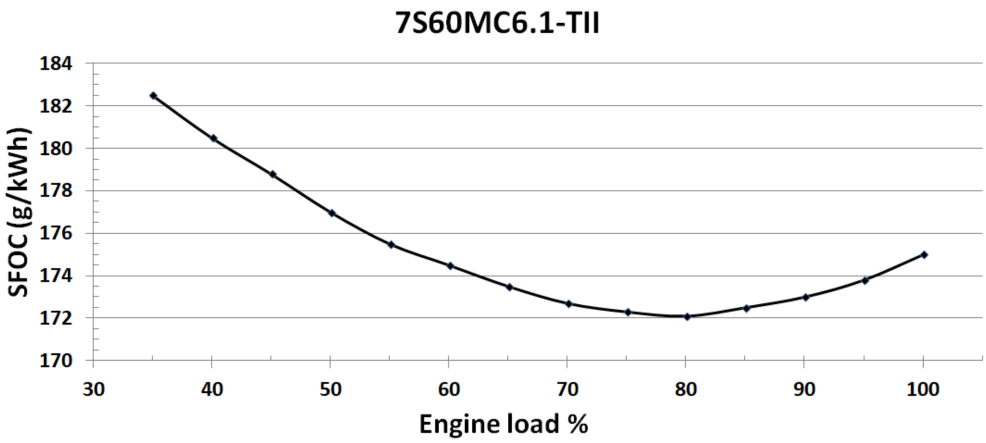


Figure 5.1 SFOC vs Engine load curve of example engine (Model engine: MAN B&W 7S60MC6.1-TII)

Based on above, the calculation flow of ship fuel consumption is shown in Figure 5.2.

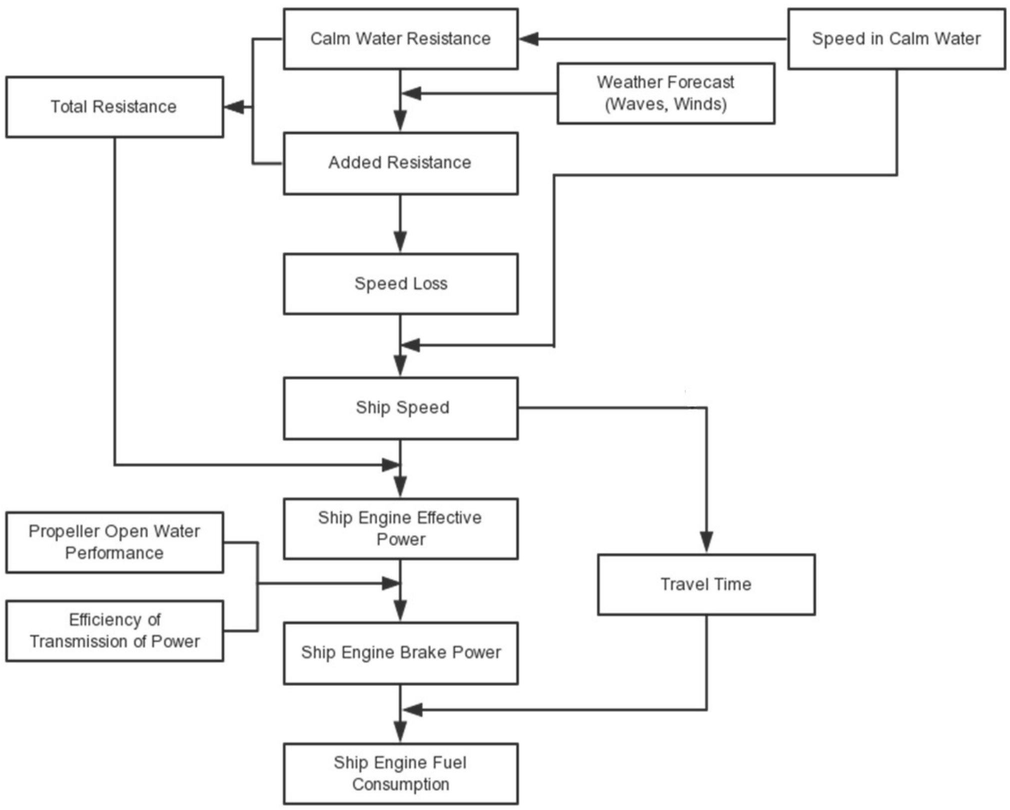


Figure 5.2 Calculation flow towards fuel consumption

The input parameters for this module include not only the ship particulars entered by the user but also the weather information at the certain waypoint passed from grids system module which is extracted from the entered shipping plan. Based on these input information and followed the calculation flow shown in Figure 5.2, the calculated ship performance can be determined by the methods introduced in Chapter 4 and this section, and then the ship performance results will be transferred to the girds system module and then be stored in the corresponding waypoint.

Besides, the sea trial data, ship model test data or even noon report data can be introduced to verify the predicted ship performance.

5.2.2 Grids system design module

Grids system is a group of networked waypoints which is designed in advance for leading the ship travel. The grids system also has a significant impact on the final weather routing result. Because different grids system means different waypoints distribution that may lead to different ship routes, and the weather data based on local waypoint will also change slightly, which will directly affect the ship's operation and then affect the fuel consumption results. The main design principle of grids system is described as below:

1. The GCR (Great Circle Route, the shortest distance between two points on a sphere) connecting the departure port and destination port is taken as the reference in this grids system;

2. This GCR is divided into several equal stages with specific numbers of points;

3. Through every point on the GCR, a straight line can be drawn perpendicular to its tangent line around the circle. Every straight line can be considered as a ship travel stage;

4. Certain numbers of points can be distributed along this vertical line with an equal interval distance, including upper and lower parts of the GCR;

The number of stages, the number of waypoints on each stage and the distance between adjacent waypoints are adjustable. The distribution of waypoints requires the user to set them in advance by experience. First of all, the distribution of waypoints should cover a large area of reasonable navigation area to ensure that the optimal navigation route is included in this grids system. Secondly, if the waypoints are dense, this will improve the accuracy of weather routing calculation, but will greatly improve the calculation amount. If the waypoints are too sparse, the calculation efficiency is high, but the accuracy of the result route will be affected. Therefore, users should consider how to design the grids system to minimise the computation amount without affecting the accuracy of the results. In addition, the ratio of the vertical distance between the adjacent waypoints on one stage to the distance between the adjacent stages should not be too large, otherwise, the shipping route will have some extreme or unreasonable situations such as zigzag shape. A typical grids system can be clearly explained in Figure 5.3.

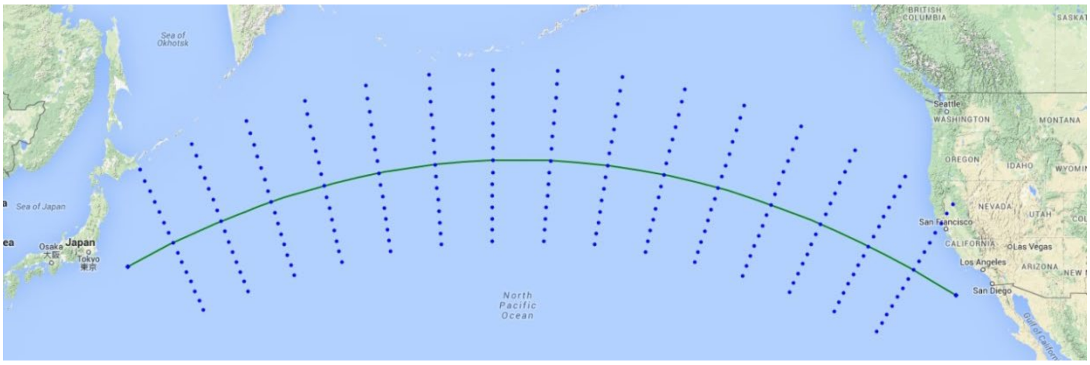


Figure 5.3 A typical grids system (Map data ©2016 Google)

5.2.3 Land avoidance function

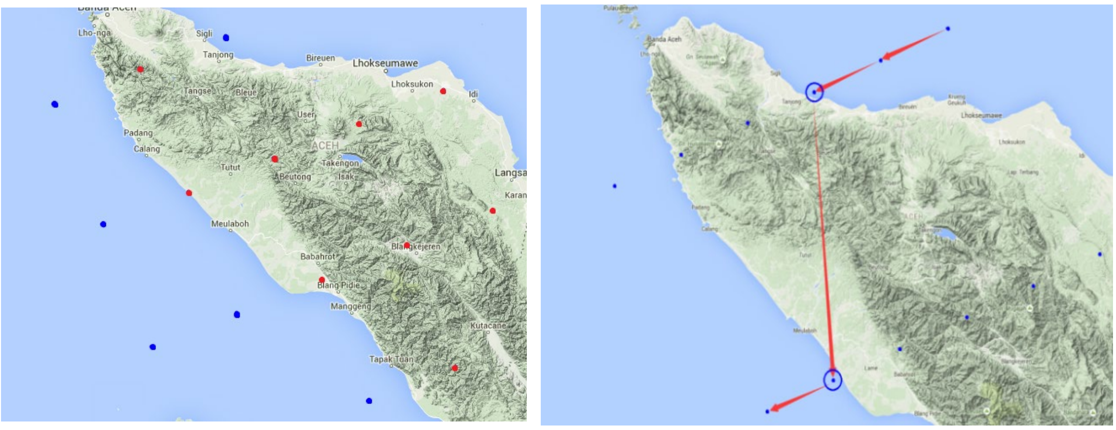
The grids system above is only suitable for open water. However, for most of the real situations, the ship always travels around some islands or needs to avoid some specialised areas like prohibited military zone. Therefore, a land avoidance method should be introduced to this module. Here, the GSHHS database is integrated within this module. In this database, every island, including the mainland, is regarded as a polygon formed by these coastline data. So once a navigable zone is decided, several polygons represented the lands, and their boundaries can be found within this area, and then the waypoints can be operated according to two rules below:

1) Based on the GSHHS coastline date, the position of each node in the grids system will be recognised as on land or in the ocean. If a waypoint is on land, that means this node is inside the polygon represented this land or located at the boundary of this

polygon; the weather routing calculation will automatically ignore this waypoint, thus the ship certainly will not go through that point.

2) As the waypoints on land will be ignored automatically, the waypoints whose connection line is passing the land also need to be ignored. This process is achieved by distinguishing the intersection between the connection line of two nodes and polygons read from GSHHS data. If two waypoints are both in the sea or one waypoint is in the sea while another waypoint is on land, but the straight line connected these two points crosses an island, in other words, there are intersections between this line and this polygon, that line will be ignored. That means the ship will not go along that line, and it will choose next available waypoints to sail.

The programming codes automatically implement all these operations. The users do not have to process each waypoint manually.



(a) Rule 1 (b) Rule 2

Figure 5.4 Land avoidance function (Map data ©2016 Google)

As presented in Figure 5.4 (a), the waypoints in red colour will be ignored automatically, while in Figure 5.4 (b), the straight line connected two waypoints with blue circle crosses the land, so 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 is developed. However, there is still more complicated situations where this simple function cannot be satisfied. For example, if all the waypoints on a stage are not satisfied with the above conditions, there will be no suitable waypoint to navigate the ship when it comes to this stage, and the trial will be terminated. Therefore, a more powerful land avoidance function is developed and its design principle is introduced as below:

1. Set an original grids system based on the above basic principle according to departure port and destination port;

2. Check if there is a stage, all the waypoints on that are unreachable or unable to pass for the ship;

3. If there is no such a stage, it means there is at least one route is available for ship navigation, then the basic grids system will be enough for weather routing simulation. If there is such a stage, then step 4 will be executed.

4. In the original grids system, there is already a perpendicular bisector of the GCR that crosses the midpoint of the circle, and a serious of waypoints have been laid on it according to the pre-set vertical resolution. The waypoints on this perpendicular bisector are extended to both sides with the same vertical resolution until at both ends of the bisector there is an end point in the ocean. The number of waypoints that extends to each side will be calculated. If the number of extended waypoints at one end exceeds 3 times the other end, then the end with a larger number will be deleted, leaving only the endpoints that reach the ocean by a smaller number. If not, then both endpoints will be kept.

5. Taking an endpoint which is extended into the ocean as an example, the departure point of the GCR and this endpoint on the bisector line are connected to form a new great circle. Based on this new great circle, a sub-grids system based on the departure point and this endpoint are made.

6. It will be checked if the new sub-grids system meets the requirement that the ship can be navigable. If not, step 4 and step 5 will be repeated for this sub-grids system until the newly generated grids system meets the requirements for navigation.

7. Next, the terminal point of the sub-grids system that meets the navigation conditions and the real destination point of the trip are connected to form a new great circle and then a new sub-grids system is built based on this new great circle. Step 6 will be repeated until a new sub-grids system that can reach the final destination is generated.

8. Connecting all of these generated sub-grids systems will form the final grids system that meets the ship navigable conditions.

9. The same process is also repeated for another endpoint in the ocean on the vertical bisector if the endpoint at the other side is retained. Then two generated grids system are compared. The grids system with shorter calculation time, shorter total distance and less waypoint is kept and the other is deleted. If their indicators are similar, the grid systems on both sides will be preserved and both of them will perform the weather routing simulation. The final optimal ship voyage plan will be determined based on all these simulations.

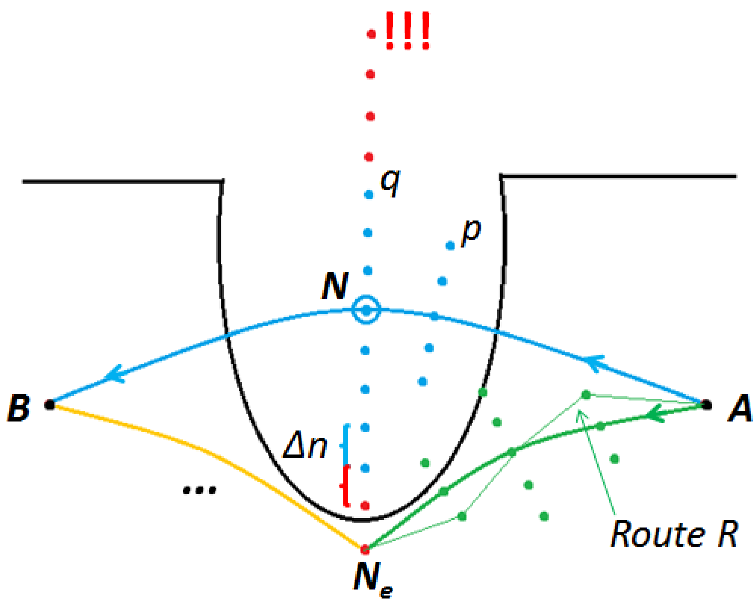


Figure 5.5 Simplified view of upgraded land avoidance function

A simple example is tested to make the upgraded land avoidance function much easier to understand which is shown in Figure 5.5, in which, point A is the port of departure, and point B is the port of destination. The blue curve connecting the two points A and B is the great circle. Based on these, a basic grid system can be established, which is shown in blue in Figure 5.5. However, it is easy to see that there is a continent between A and B (black). If a ship travels from A to B, when it reaches stage p, all the waypoints on this stage are on the mainland and the ship cannot pass. In this case, several steps will be followed:

1. The land avoidance function will find the vertical bisector of this great circular route firstly. It crosses the midpoint *N* (the node with a blue circle) of the great circle. The waypoints on this line also form the middle stage of the entire route: stage *q*.

2. Extend the waypoints on stage *q* toward both ends with the original vertical resolution Δn, as shown in red in the figure. For the upwards extension, due to the excessive number of extended waypoints, this side is not considered and is indicated by the red "!!!" in the figure. In the other side, the waypoint will keep extending downwards until there is a point in the ocean, that is point N_e as shown in the figure.

3. Reconnect two points *A* and N_e, so a sub-grids system between these two points can be built according to the basic principles, as shown in green.

4. Check if the ship can pass this sub-grids system smoothly. The figure shows that there is at least one route: *Route R* for the ship to can pass through, which indicates that this sub-grids system can remain.

5. Connect N_e and the final destination *B*, and keep repeating the above process until all newly-created sub-grids systems meet the ship navigable conditions. The repeat process is indicated by a black ellipsis "…" and marked by orange in the figure.

6. All sub-grids systems are grouped to form a complete grids system and finally imported into the weather routing system for calculation.

In this way, the ship can successfully avoid the mainland or islands when it travels from *A* to *B* by the upgraded land avoidance function.

Working principles of upgraded land avoidance function in the real world is shown in Figure 5.6. In this figure, the shipping area in southern Africa is taken as an example. As can be seen from the figure, this upgraded land avoidance function works well for this area, the ship can successfully travel from West Coast of Africa to East Coast of Madagascar or the return route based on the generated grids system. It's worth noting that the grids systems of forward and backward direction may be different. As to why the number of waypoints on each stage is gradually changed, the reason is explained in Section 6.2.2 of the next chapter.

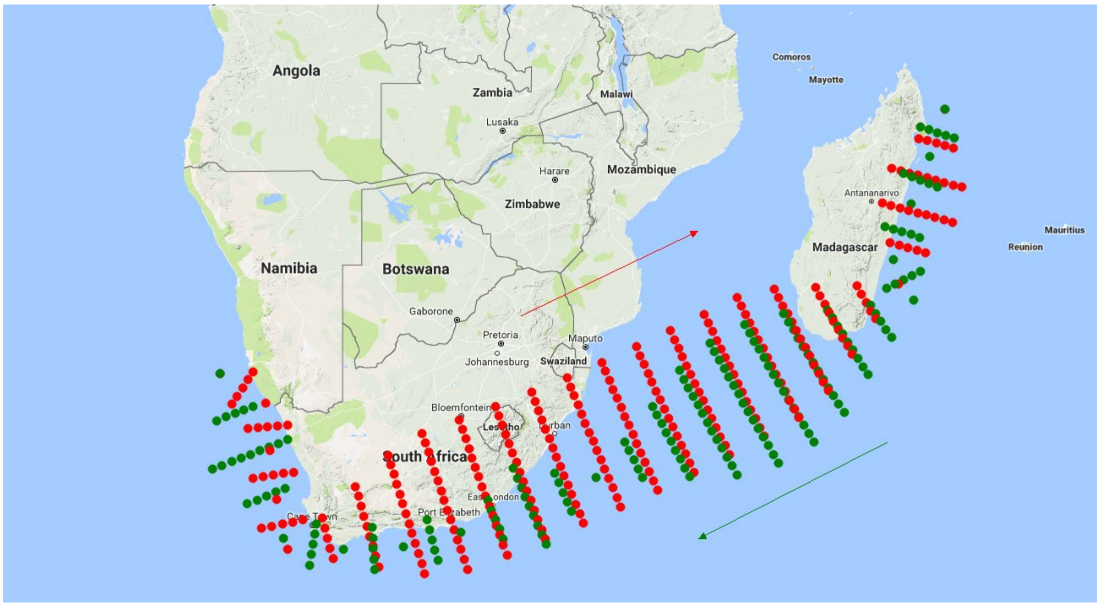


Figure 5.6 Effect of upgraded land avoidance function working in southern Africa (Map data ©2016 Google)

Based on this land avoidance function, most of the navigational routes in the world can be satisfied.

5.2.4 Weather data module

The 36 years (1979-2014) global historical weather data are downloaded from the ECMWF website and stored in the weather data module. The data file is constructed in gridded binary (GRIB) form with various weather attributes integrated. Since the weather routing system only takes winds, waves into account at the moment, the related weather data will be decoded by files reading functions in the weather data module. Among them, five weather attributes: 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 are extracted. All these attributes are updated every 6 hours in one day and are distributed in the ocean at a geographical resolution of $0.75° \times 0.75°$. All of these weather data files also contain attributes of time, latitude and longitude.

After the navigation plan is confirmed, the navigation time and navigation area are also determined. When the ship sails to a particular place at a specific time, the weather data module will receive the geographical and time information from the grids system module, and then decode and search the corresponding weather data based on this information. After the corresponding weather information is determined, they will be passed back to the specific waypoint in the grids system module for the subsequent calculation of the ship performance.

5.2.5 Ship safety module

This is a very important module since it makes sure that the safety of the ship and crew are addressed to ensure that ship safety is not comprised while energy efficient ship operation is planned. Seakeeping performance is introduced in the ship safety module to guarantee the ship navigation safety.

As mentioned in Section 4.5, four parameters are calculated according to NORDFORSK criteria (1987) in this module. They are:

- Probability of slamming;
- Probability of deck wetness;
- RMS of roll;
- RMS of relative vertical acceleration at FP.

The detailed calculation information of these parameters has been introduced in Section 4.5. All of them should be less than corresponding criteria according to different navigation situation. During the calculation process, the core of the calculation is the transfer functions of different motions, as all of four seakeeping performance measurement are calculated based on their corresponding transfer functions. Calculating the transfer functions in hydrodynamic software is a relatively simple method. A transfer function file can be obtained from the hydrodynamic software, which contains transfer functions values of different motions. Users can search corresponding transfer function values according to the given ship speed, ship heading and wave period value by files reading function. Here only three motions, heave, roll, pitch, are taken into consideration. Then the value is passed to the ship safety module to calculate the ship's seakeeping performance. The result whether the seakeeping performance indicators meet the corresponding requirement or not will be fed back into grids system, so that the ship operation can be adjusted according to the result.

Seakeeping performance can be regarded as a constraint condition for the following optimisation. If the sea condition of a certain area does not satisfy the ship's navigation requirements, a "Dangerous" signal will be assigned to that ship operation, which refers to either ship speed or ship heading or both. For example, if according to the weather forecast, it is known that there will be severe waves in the sea at some time in the future, which will be detrimental to the ship safety, then through the prediction of the ship safety, operators can decide to let the ship accelerate through the sea before the large storms arrive, or to decelerate immediately until the storm passed that area, then go through the sea at normal speed, or simply change ship course so that the ship can avoid the dangerous area.

5.2.6 Weather routing module

Weather routing can be viewed as voyage optimisation considering weather factors. The weather routing module is the core module of the whole system. In this module, since the system is developed towards energy efficiency, the voyage optimisation strategy adopted is a combination of global and local optimisation with two objectives: ETA and fuel consumption.

As can be seen from the grids system in Figure 5.3 and Figure 5.7, the entire ship sailing route can be divided into several stages, and the ship can travel towards the destination stage by stage. There are many waypoints distributed at each stage. These waypoints can be regarded as both the departure point to the next stage and the arrival point from the previous stage. The ship departing at each point can sail to all possible waypoints at the next stage. Therefore, there are many potential route segments between every two stages.

The steps of weather routing are introduced as below and the calculation starts from the departure point.

1. The module reads the weather data at the departure point by local longitude, latitude and departure time.

2. Because there are many possible waypoints on the next stage, thus, there are many possible directions from the departure point to the next stage. These directions also represent the ship headings. A speed value is assigned in either direction. This speed

starts at the minimum speed and traverses to the maximum speed at ΔV intervals. The operator pre-sets the range of speed change.

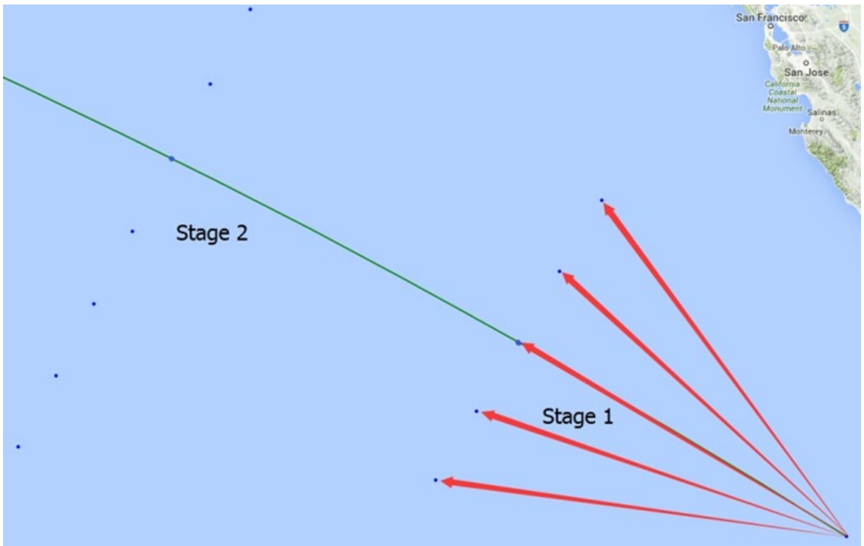


Figure 5.7 Ship routing stages (Map data ©2016 Google)

3. With the given weather data, ship speed and heading, the fuel consumption of this route segment under this condition can be easily calculated based on the fuel calculation method integrated into the ship performance calculation module.

4. Then the ship navigation information of this segment under the corresponding conditions is saved at the arrival waypoint of the route segment. This information includes fuel consumption on this segment, total fuel consumption of the entire trip, ship speed, sailing time on this segment, local time and geographical coordinates of the corresponding departure point. Here, the local time is calculated by taking into account the departure time plus sailing time on this segment.

5. Next, the arrival point of the previous stage becomes the departure point for the next new stage. Based on the original stored information at this new departure point, the new weather data will be read, and the new speed will be assigned to any direction to the next stage. Then a new round of calculations is performed for the navigation of next stage. As with the previous method, the result is also stored in the corresponding arrival waypoint in the next stage.

6. Based on the same method, fuel consumption calculations are repeated on all stages until the navigation information of the last stage is calculated. The entire

calculation process will cover all possible route choices and will traverse all possible ship courses between two stages and all speed options in each route segment.

7. After calculation, except the original departure point, each point will store a large number of groups of navigation information. Some of this information is for the current route segment, and some are accumulated information for all past sailing process. Therefore, each set of data in one waypoint can represent the navigation information of a potential route that the ship has passed through from the original departure point, under a certain navigation condition.

8. In the end, the total fuel consumption and voyage duration of different potential route with different voyage plan will be stored in the waypoint represented destination. By checking the navigation information stored in final destination point, a Pareto front (ETA vs. Fuel consumption) for the entire voyage can be drawn. And then an optimal voyage plan with minimum fuel consumption can be selected according to the ship navigation schedule (ETA), which will be implemented in post-processing module. The whole process can be regarded as a global optimisation.

When a ship travels from one stage to the next, the weather routing module will produce a large number of different ETA and fuel consumption combinations, as the module will traverse so many speed and direction options. As mentioned above, all of this massive amount of information will be saved at the arrival point of this stage. When the ship sails to the next stage, these arrival points become the starting point, and the information saved there becomes the initial information for the ship's next navigation. The navigation of the ship to the next stage needs to be based on these initial information. If there are a large number of initial messages from the previous stage which means that there are many potential voyage plans obtained from the previous stage, as the ship will perform subsequent calculations based on each voyage plan, this will lead to an increase in the number of calculations in each stage.

As a simple example, assuming that there are always 10 operation combinations including different speed and direction for the ship goes to the next stage from each initial information. Evidently, at the original departure point, as can also be regarded at stage 0, there is only one initial sailing condition because the departure time and position are fixed and total time and fuel consumption are both zero. When the ship sails to the next stage, considering that there are 10 different operation combinations, then in the next stage, which is stage 1, there are 10 possible voyage plans stored. And when the ship sails toward the second next stage, the number of initial information becomes 10, as there are still 10 different operation plans for each initial information at stage 1, the number of potential voyage plan at stage 2 becomes 100. If continuous iteration lasts until final destination point, the number of final results will be extremely large. This is only a simple assumption. Considering that there are many speed options and direction options, the real prediction will not have only 10 combinations of operations for each initial condition, so the actual amount of computation will be prohibitively large. This will lead to very much computational time.

Here, local optimisation strategy is introduced. For anyone of the relative arrival points, it will store a lot of navigation information about ETA and fuel consumption from the previous stage. In this information, there must be some voyage plans with the same ETA but different fuel consumption. Obviously, all other voyage plans except the one with minimum fuel consumption are meaningless under each same ETA condition. It is easy to understand that they use the same ETA to reach the same location but consume more fuel. So these redundant results can be deleted, and only their corresponding navigation information with the minimum fuel consumption value is reserved for each different ETA value. Here, assuming that critical safety conditions are automatically eliminated. That is, keeping a Pareto front of ETA and fuel consumption for each relative arrival point, as can be seen in Figure 5.8. Thus, when this point is regarded as the starting point for the next stage of sailing, only the navigation information retained on the Pareto front is calculated, instead of all the information stored at this point is calculated. Therefore, this strategy will reduce the overall system calculation costs.

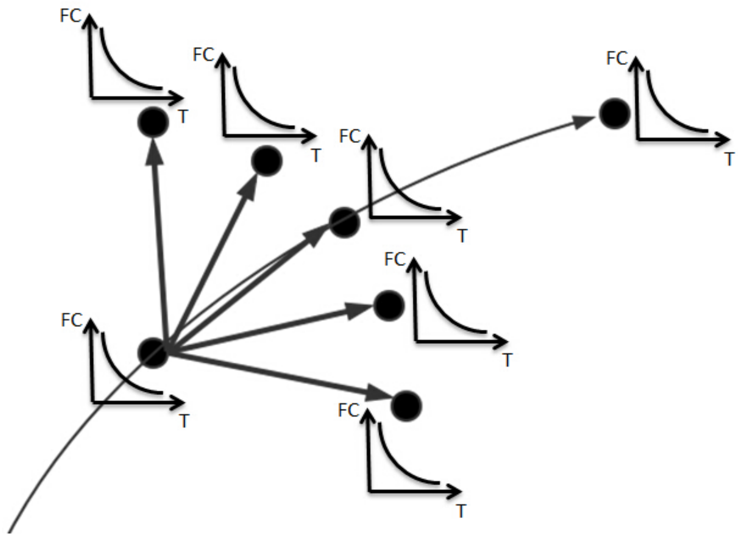


Figure 5.8 Local optimisation strategy

From another point of view, each of the relative arrival points can be regarded as a temporary sailing destination point. In the global optimisation, a Pareto front is extracted from the information stored at the true destination point, so that at the end of each temporary voyage, a Pareto front can be also extracted on every temporary destination point without affecting the final result, and all other insignificant results can be deleted to save computational costs.

This process can be regarded as a local optimisation. So the whole weather routing strategy can be viewed as a combination of global and local optimisation.

The proposed weather routing algorithm can also be expressed mathematically.

As mentioned above, each available waypoint will save this information for weather routing calculation: total fuel consumption during the past trip, fuel consumption on last segment, local time, sailing time on the last segment, ship speed on last segment and the position of corresponding departure point on the last stage.

Several letters and mathematical symbols can be introduced to describe these variables. Here, k represents the stage the ship arrived and n represents the index of vertical waypoint on one stage. Assuming the total number of stages is K, and the total vertical waypoints on one stage is N. Thus, $k \in [0, K]$ (departure stage is Stage 0) and $n \in [1, N]$.

Moreover, $FC(k,n)$ is the total fuel consumption when the ship arrived the waypoint $P(k,n)$, $\nabla FC(k,n)$ is the ship fuel consumption from waypoint $P(k-1,*n)$ to $P(k,n)$, $*n$ is index of the vertical waypoint in the last stage, $T(k,n)$ is the local time, $\nabla T(k,n)$ is the ship sailing time from waypoint $P(k-1,*n)$ to $P(k,n)$, $V(k,n)$ is the ship speed sailing from waypoint $P(k-1,*n)$ to $P(k,n)$.

Since the weather routing algorithm aims to solve the minimum fuel consumption problem in this research, the calculation principle can be introduced starting from $FC(k,n)$:

$$FC(k,n) = FC(k-1,*n) + \nabla FC(k,n) \tag{5.5}$$

Equation 5.5 shows that the total fuel consumption at the waypoint $P(k,n)$ can be calculated by sum of the total fuel consumption at waypoint $P(k-1,*n)$ and the fuel consumption between two waypoints $P(k,n)$ and $P(k-1,*n)$. Here, the calculation of $\nabla FC(k,n)$ can be described as below:

$$\nabla FC(k,n) = f\left(W(k-1.*n), V(k,n), \nabla D(k,n), S(k,n)\right) \tag{5.6}$$

which means the fuel consumption between two stages can be determined by local weather data $W(k-1,*n)$, the ship speed $V(k,n)$ and distance $\nabla D(k,n)$ between two waypoints $P(k,n)$ and $P(k-1,*n)$, and ship parameters $S(k,n)$ including ship particulars and propeller and engine parameters. Here, the ship particulars are fixed when the ship model is determined. However, the propulsion efficiency, engine load, engine RPM and Specific Fuel Oil Consumption of the engine will change with the variables like ship speed and weather conditions. So ship parameters are defined as $S(k,n)$.

Among them, $\nabla D(k,n)$ can be determined by the positions of waypoint $P(k,n)$ and $P(k-1,*n)$, which is described as:

$$\nabla D(k,n) = d\left(P(k,n),\ P(k-1,*n)\right) \tag{5.7}$$

The local weather data $W(k,n)$ can be determined by the local position and local time, which can be described as:

$$W(k,n) = w\big(P(k,n), T(k,n)\big) \tag{5.8}$$

where, local time $T(k,n)$ can be described as:

$$T(k,n) = T(k-1,{*}n) + \nabla T(k,n) \tag{5.9}$$

This means the local time at the waypoint $P(k,n)$ can be calculated by sum of the local time at the waypoint $P(k-1,{*}n)$ and the ship sailing time $\nabla T(k,n)$ between two waypoints $P(k,n)$ and $P(k-1,{*}n)$. Moreover, $\nabla T(k,n)$ can be calculated by the following formula:

$$\nabla T(k,n) = \frac{\nabla D(k,n)}{V(k,n)} \tag{5.10}$$

To sum up, the fuel consumption at the waypoint $P(k,n)$ can be clarified as relevant to the positions of waypoint $P(k,n)$ and $P(k-1,{*}n)$, $V(k,n)$ and ship parameters $S(k,n)$. Thus,

$$FC(k,n) = fc\big(V(k,n),\ P(k,n),\ P(k-1,{*}n), S(k,n)\big) \tag{5.11}$$

For the global level optimisation, the optimisation process can be expressed as below:

Final objective: $\quad Minimise: \ FC\big(K,\ (N+1)/2\big)$

((*N*+1)/2) means the middle vertical waypoint on one stage)

Initial conditions: $\quad T\big(0,\ (N+1)/2\big) = input\ departure\ time$;

$$FC\big(0,\ (N+1)/2\big) = 0;$$

Subject to: $\quad T\big(K,(N+1)/2\big) = T\big(0,\ (N+1)/2\big) + ETA$;

ship safety criteria in seaway;

waypoints are available for ship sailing;

$$V \in [V_{min}, V_{max}];$$

$$k \in [0, K];$$

$$n \in [1, N];$$

The global optimisation will cover all possible *V*, *k*, *n* variables.

For the local level optimisation, the optimisation process can be expressed as below:

Local objectives: $\quad Minimise: \ FC(k,n)$ under each possible $T(k,n)$

Initial conditions: $\quad T\left(0,\ (N+1)/2\right) = input\ departure\ time;$

$$FC\left(0,\ (N+1)/2\right) = 0;$$

Subject to: ship safety criteria in seaway;

waypoints are available for ship sailing;

$$V \in [V_{min}, V_{max}];$$

$$k \in [0, K];$$

$$n \in [1, N];$$

This means that on the basis of global optimisation, a local optimisation should also be carried out on each waypoint towards the objective of minimum fuel consumption. A Pareto front of fuel consumption vs sailing time is generated on each waypoint. Thus, the optimal results under all possible sailing time should be retained. Because at the local level, every minimum fuel consumption result under each possible sailing time may be part of the result of the final optimal voyage plan.

Based on above, the final minimum fuel consumption voyage plan based on the given ETA can be obtained by this combination of the global and local optimisation algorithm.

The proposed optimisation strategy borrows ideas from another two weather routing algorithms. In the weather routing optimisation, the entire navigation process is divided into several stages, and the speed and direction variables are set for each stage, and forward recursion iteration strategy from the departure to the destination is adopted to calculate the optimum results. These strategies draw on the idea of dynamic programming algorithm. Besides, two objectives optimisation strategy and the concept of Pareto front are derived from evolutionary algorithms. Compared to other weather routing methods, the proposed method uses an easy-to-understand traversing method. Only two optimisation variables (ship speed and directions) and introducing local optimisation strategy have greatly improved the computational efficiency of the optimisation method. This method also has a full consideration of the weather, which leads the optimisation results to be more reasonable. The proposed optimisation method achieves the automatic optimisation of speed and direction and realises simultaneous voyage optimisation from both global and local levels. The local optimisation strategy makes the ship consider the speed according to the local weather at each stage, while the global optimisation strategy can make the ship plan the speed and heading from a global perspective, which also makes some less conventional but reasonable and effective voyage plans such as drastically changing course or unusual acceleration or deceleration are successfully achieved.

It is worth mentioning that since this research mainly focuses on energy efficiency, this module only focuses on two objectives: ETA and fuel consumption. If the user has other considerations, this module can be easily modified to calculate other target variables according to user requirements. For example, this module can even generate the safest route, the route with average minimum wave heights or the route most suitable for wind propulsion and so on.

5.2.7 Post-processing module

The post-processing module aims to extract all navigation data for a selected voyage plan and to visualise the corresponding route on the map. Users can use this module to obtain the results they want.

In this module, a backward iteration algorithm is introduced.

As mentioned above, on the one hand, each waypoint will store a lot of navigation information after calculation. For a piece of navigation information, it includes the total time spent and the total fuel the ship has consumed since the initial departure point, the partial time, partial fuel consumption and speed from the last stage and the coordinates of the corresponding departure point at the previous stage.

On the other hand, at the end of the calculation, there is a Pareto front on final destination point about ETA and fuel consumption. There are many potential optimal voyage plans on this Pareto front, which are the voyage plans with the minimum fuel consumption for each different ETA. According to the user's requirements, once a suitable ETA is selected, its corresponding minimum fuel consumption is also determined along with it, and its corresponding optimal voyage plan is also uniquely determined.

The backward iteration algorithm starts from the optimal result selected on the final destination waypoint. Based on the saved navigation information of this result, the coordinates of the departure point in the previous stage can be determined first. That is, from which point in the previous stage the ship sailed to this destination point. At this identified departure point, as mentioned in Section 5.2.6, there is also a Pareto front that stores navigational information from its previous stage. The next is to find which navigation information in this local Pareto front leads to the user's selected result in the end point. Returning to the end point, the selected result, in addition to storing the above coordinates, also contains two sets of important information: total fuel consumption and the partial fuel consumption from the previous stage, total time spent and the partial time spent from the previous stage. Calculating the difference between the two groups of information separately will obtain the total fuel consumption and total time spent of the ship sailing up to the previous stage. Searching with the first keyword 'total time spent' and second keyword 'total fuel consumption' on the information stored in the Pareto front of the identified waypoint, only one matched result can be found. In this way, the result is the navigation information to be found that leads to the user-selected result at the end point.

Similarly, this result also stored the same types of information generated from its last waypoint. Repeating this procedure to the initial departure waypoint, all necessary information of selected voyage plan can be obtained, including coordinates of every passed waypoint, time spent, fuel consumption and speed between every two stages.

Explaining it again with a graph will make this process clearer. As can be seen in Figure 5.9, the ship navigation starts at the departure point on Stage 0, passes Stage 1, ... , Stage K-1, and finally arrives at the destination point on Stage K. The results on the Pareto front in the destination point have been arranged in a certain order, as shown in Table (a). Assuming that Result 2 is the optimal voyage plan (shown in blue bold) that satisfies the user's requirements, and then the information of Result 2 is checked and two attributes it contains can be found: latitude last stage and longitude last stage, their corresponding values are respectively Lat_L_2 (K) and Lon_L_2 (K). These two values are also the coordinates of the departure point on the previous stage. According to these two coordinate values, the corresponding point in the previous stage can be found and it can be assumed that this point is the red point in the figure. Then there is also a Pareto front stored in this red point, and its results have also been arranged in order, as shown in Table (b). Back to the end, continue to view the other four important attributes in result 2:

- Total fuel consumption: FC total, $\text{FC\_T\_2}\left(\text{K}\right)$;
- Fuel consumption from the previous stage: FC last stage, $\text{FC\_L\_2}\left(\text{K}\right)$;
- Total time spent: ETA total, $\text{ETA\_T\_2}\left(\text{K}\right)$;
- Time spent from the previous stage: Duration last stage, $\text{ETA\_L\_2}\left(\text{K}\right)$.

The difference values of the above two sets of data are respectively calculated, which can be described by

$$\text{m} = \text{FC\_T\_2}\left(\text{K}\right) - \text{FC\_L\_2}\left(\text{K}\right) \tag{5.12}$$

$$\text{n} = \text{ETA\_T\_2}\left(\text{K}\right) - \text{ETA\_L\_2}\left(\text{K}\right) \tag{5.13}$$

Where, m and n respectively represent the total fuel consumption and total time spent when the ship travelled to Stage K-1. Back to the red point at the previous stage, n and m are used respectively as the first keyword and the second keyword to search in Table (b). It can be found that there is only one result that can match the two keywords. Suppose this result is the fourth set of results in Table (b), that is Result 4 (shown in red bold), which means:

$$\text{FC\_T\_4}\left(\text{k-1}\right) = \text{m} \tag{5.14}$$

$$\text{ETA\_T\_4}\left(\text{k-1}\right) = \text{n} \tag{5.15}$$

In other words, the Result 4 in Table (b) leads to the Result 2 in Table (a). So that the ship sailing information of the previous stage relative to Result 2 is successfully found. The same calculation is repeated until it reaches the initial departure point. In this way, all navigation information of this voyage plan corresponding to Result 2 in Table (a) will be extracted.

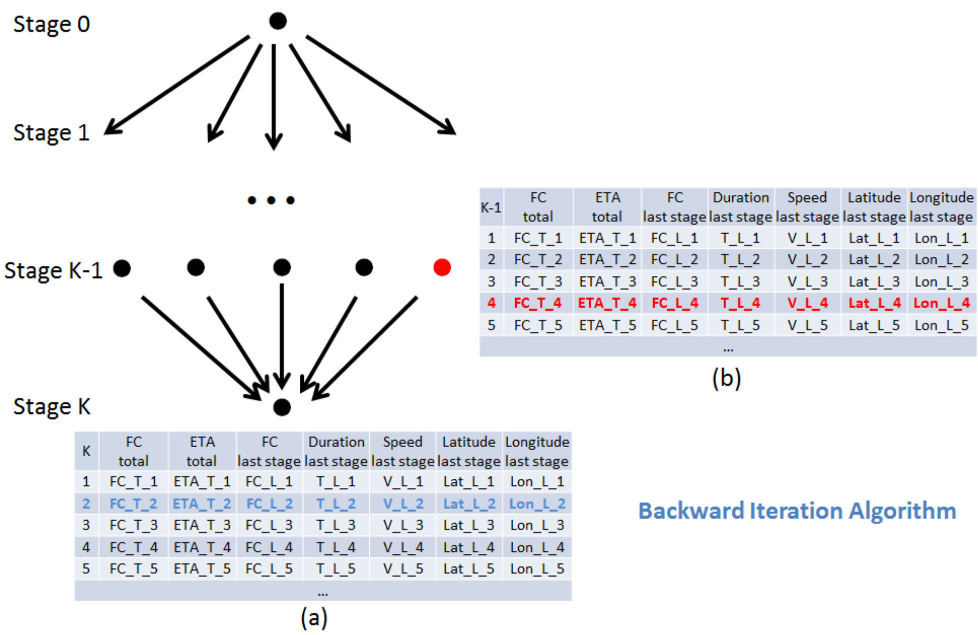


Figure 5.9 Backward iteration algorithm in the post-processing module

If necessary, this module can even provide detailed weather data at each waypoint when the ship is passing by. In this module, the only input required is the selected ETA, if that is decided, all the information of its corresponding voyage plan will be extracted for the system users.

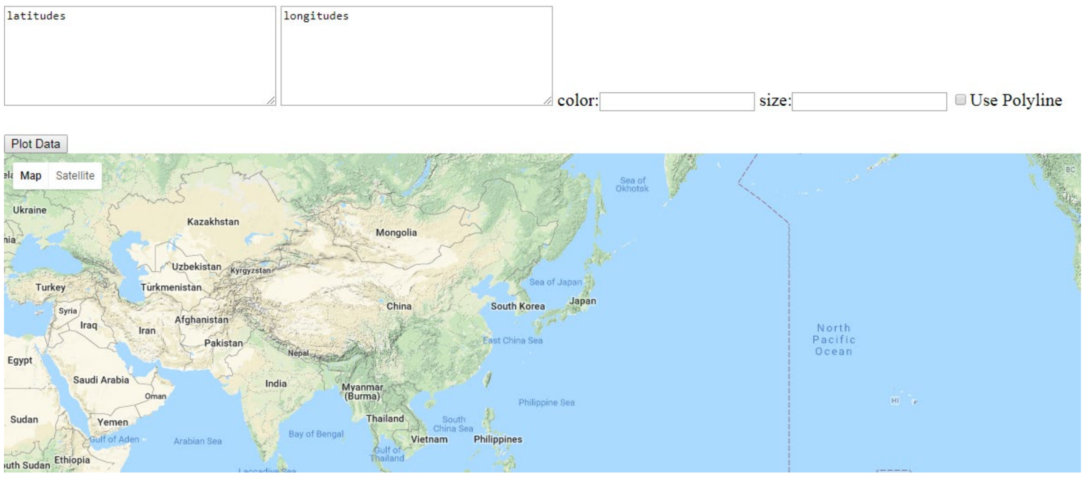


Figure 5.10 Route visualisation tool (Map data ©2014 Google)

When the waypoints for the entire route are determined, their coordinates are also determined. A Google Maps based route display tool is introduced to this module for visualising the objective route on the real map, which can be seen in Figure 5.10. Users need to enter the latitude and longitude coordinates of all the waypoints to this tool, and select to connect them with a smooth curve, set the width and colour of the route, then the calculated route, which is also the user's desired route, will be displayed on the map.

5.3 Case Study

Several case studies are carried out to preliminarily verify the weather routing system. In these case studies, a 115K DWT Crude Oil Tanker (Aframax COT) is taken as the ship model. The main particulars of the ship, main engine and propeller are given in Table 5.1.

Table 5.1 Main particulars of 115K DWT COT

Model	Unit	115K COT
Ship Type	-	Tanker
L_{pp}	m	249.8
B	m	43.8
T	m	12.5
Main engine type	-	MAN B&W 7S60MC
Propeller Diameter	m	7.35 (F.P.P.)

Before conducting the case study, the ship brake power performance in calm water predicted by the proposed system should be validated with sea trial data firstly. The validation is carried out for two loading conditions (ballast and scantling) of the ship. Here, the speed ranges are set according to the sea trial report. The comparison results under different conditions are shown in Figure 5.11.

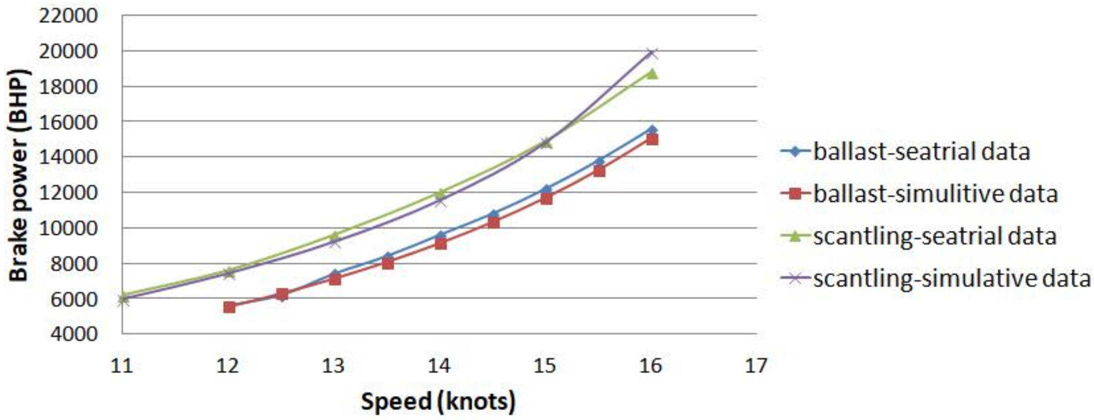


Figure 5.11 Speed vs brake power curves in calm water comparison

As can be seen from Figure 5.11, the simulated brake power vs speed curves for both ballast and scantling loading conditions are in agreement with those curves in sea trial report. Closer observation of the results reveals that the simulated brake power values are average 3.13% less than sea trial data between 12 knots and 16 knots under the ballast loading condition, while this difference is average 1.01% less between 11 knots and 16 knots under the scantling loading condition. It can be considered that these errors are acceptable for the calculation of ship brake power performance in calm water.

Following that, the FCR (tonnes/hour) of this ship under various speed and weather conditions is simulated based on the proposed approach and compared to performance of the ship during the actual voyage. Here, the FCR values for various weather conditions for the route between Freeport (Texas) and Puerto la Cruz are extracted from the noon reports and compared against the simulated results. This is the most repeated routes in the noon report, and therefore it will record more results which can minimise the randomness of recorded values. Analysis of noon reports revealed that, in Ballast Condition (Freeport (Texas) - Puerto la Cruz), the ship always met head sea and bow sea states, while in Laden condition (Puerto la Cruz - Freeport (Texas)), the ship always met beam sea and following sea states. Several most common sea states during this route are extracted for validation. The comparison of recorded FCR results and simulated FCR results under different speed, weather and loading conditions are shown in the following figures (Figure 5.12 to Figure 5.22).

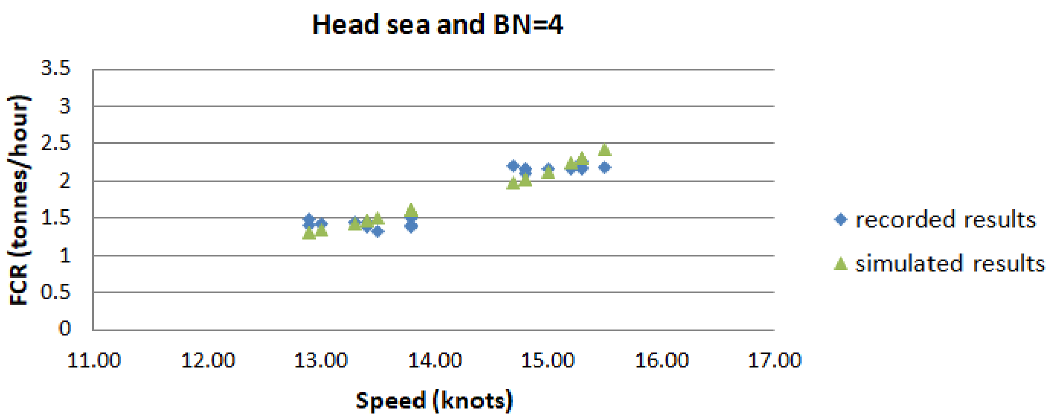


Figure 5.12 Validation results for head sea and BN = 4 (Ballast Condition)

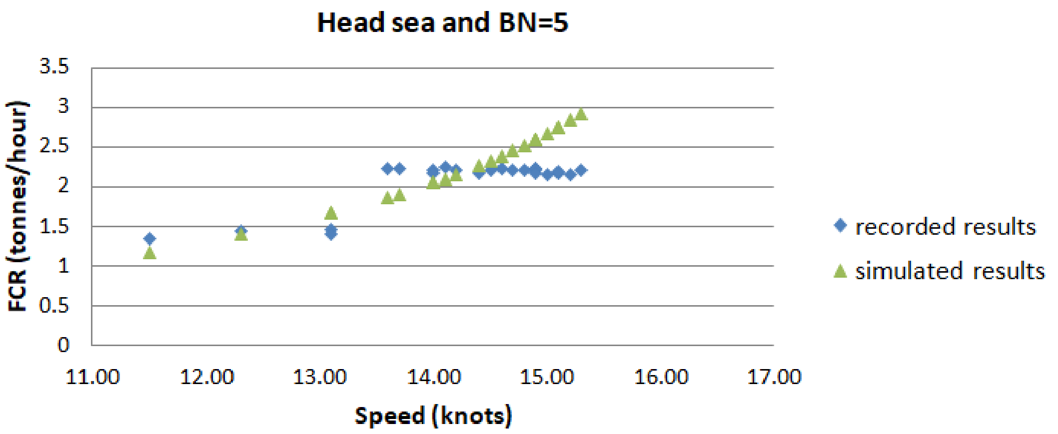


Figure 5.13 Validation results for head sea and BN = 5 (Ballast Condition)

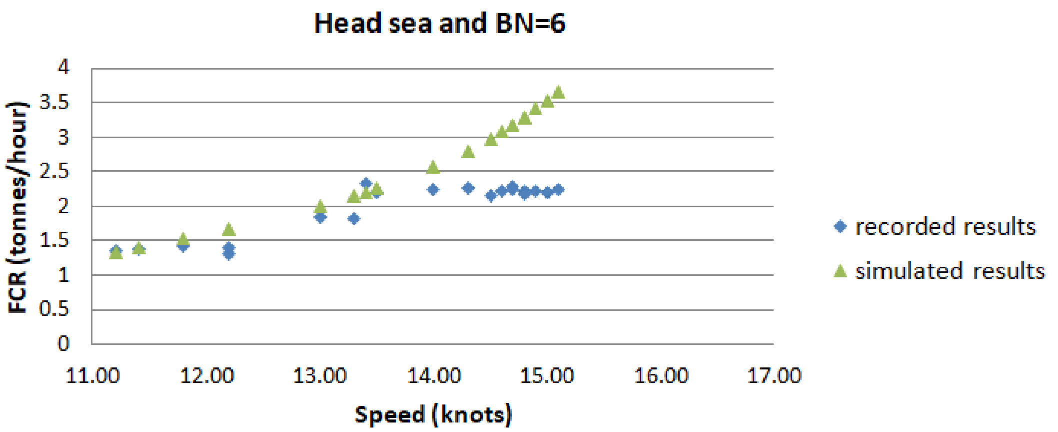


Figure 5.14 Validation results for head sea and BN = 6 (Ballast Condition)

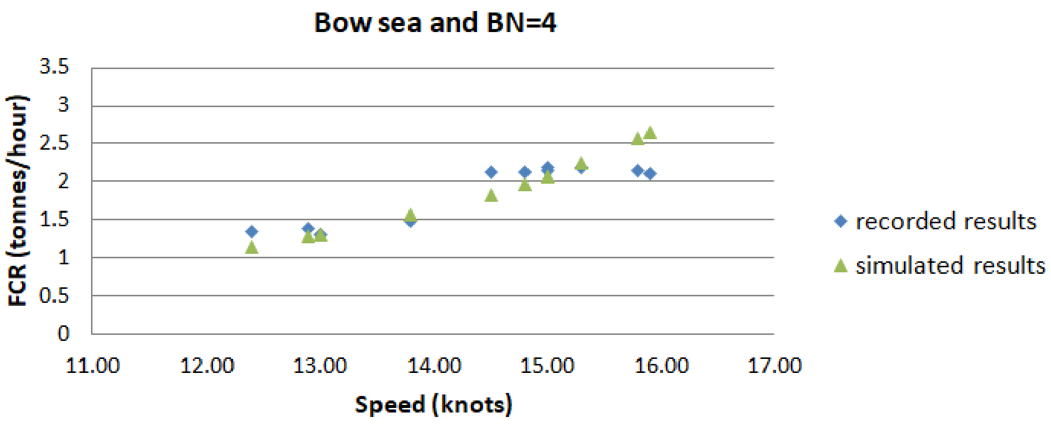


Figure 5.15 Validation results for bow sea and BN = 4 (Ballast Condition)

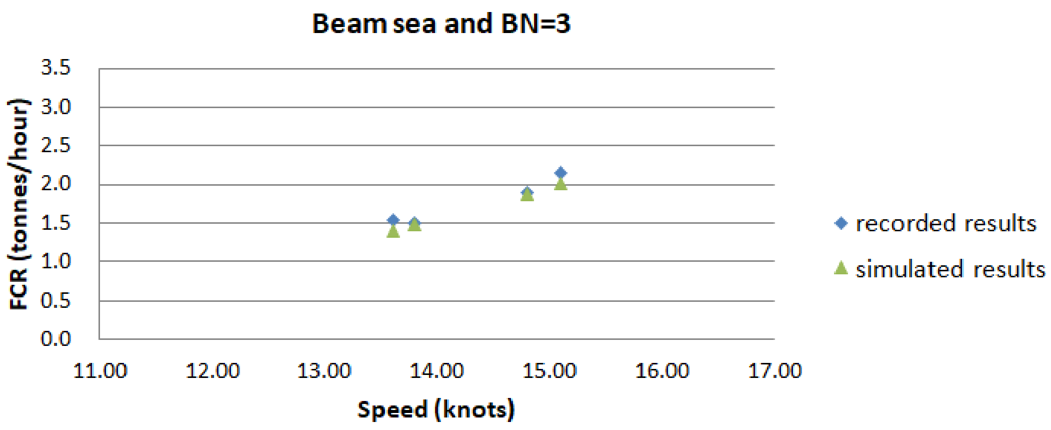


Figure 5.16 Validation results for beam sea and BN = 3 (Laden Condition)

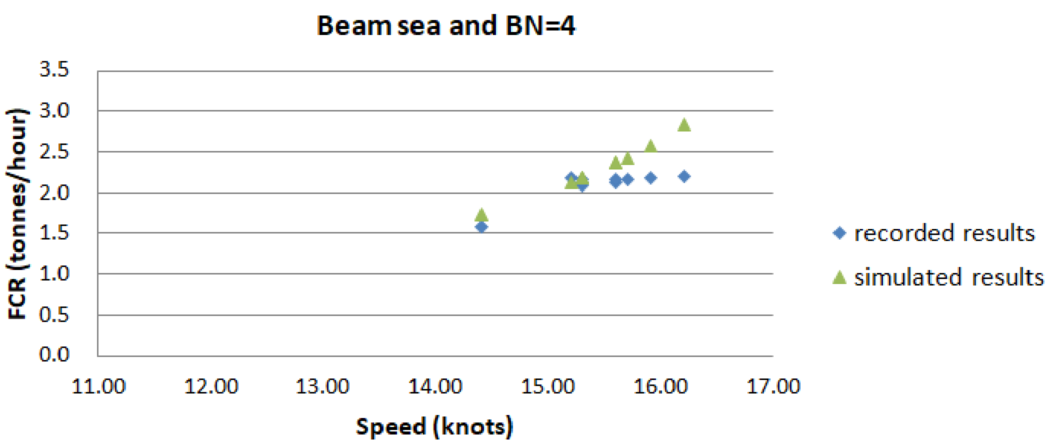


Figure 5.17 Validation results for beam sea and BN = 4 (Laden Condition)

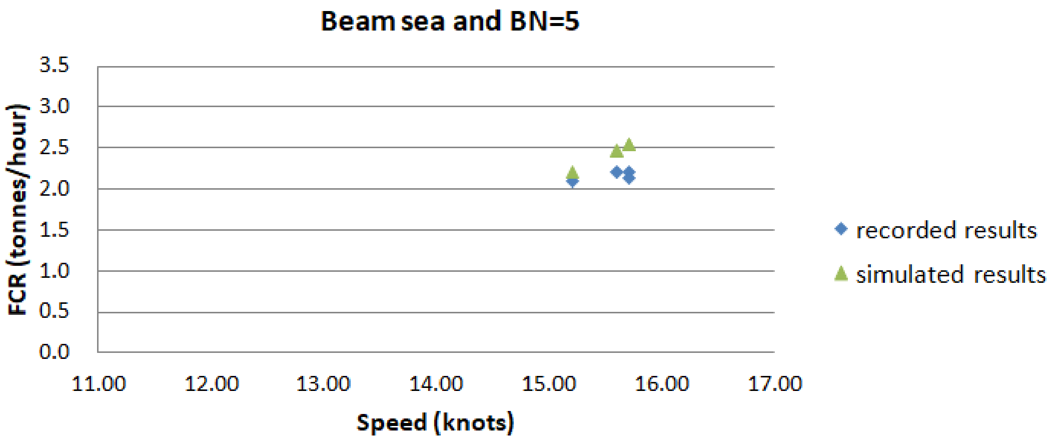


Figure 5.18 Validation results for beam sea and BN = 5 (Laden Condition)

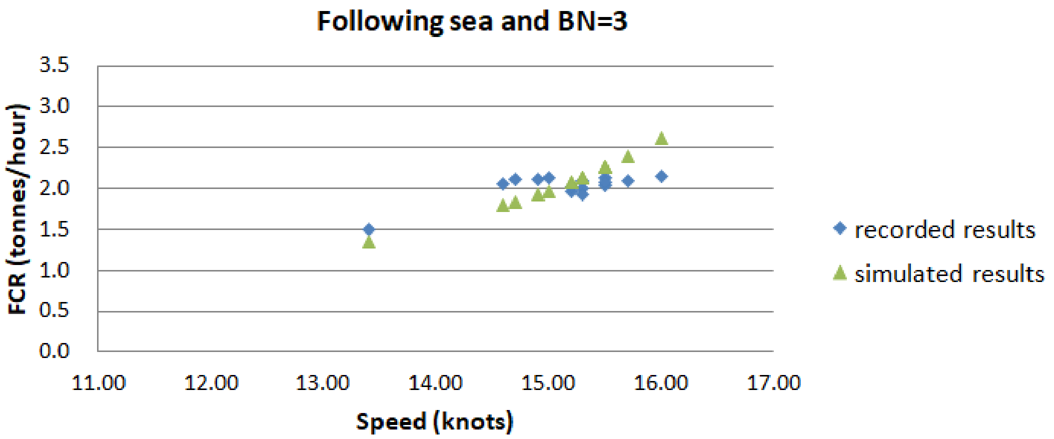


Figure 5.19 Validation results for following sea and BN = 3 (Laden Condition)

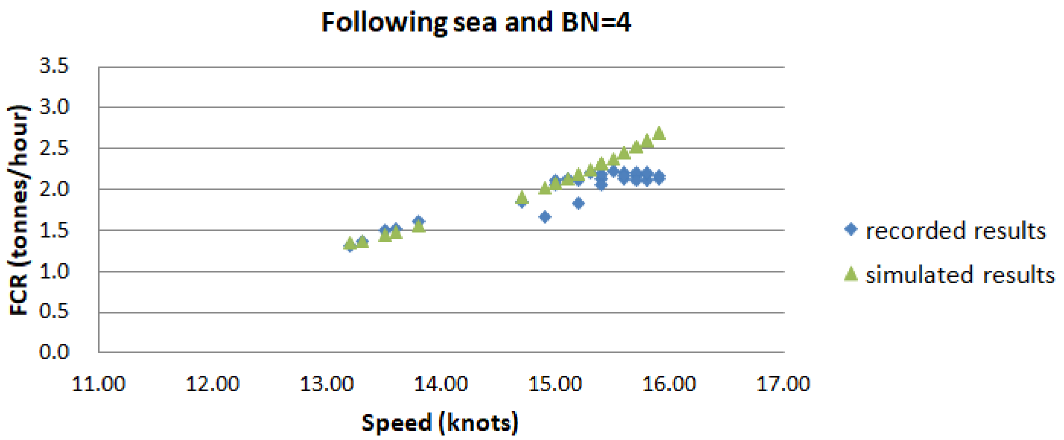


Figure 5.19 Validation results for following sea and BN = 4 (Laden Condition)

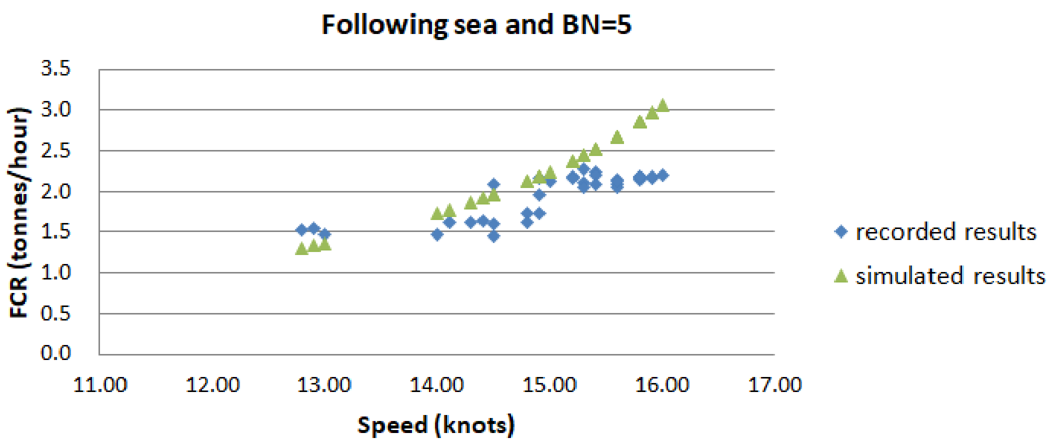


Figure 5.20 Validation results for following sea and BN = 5 (Laden Condition)

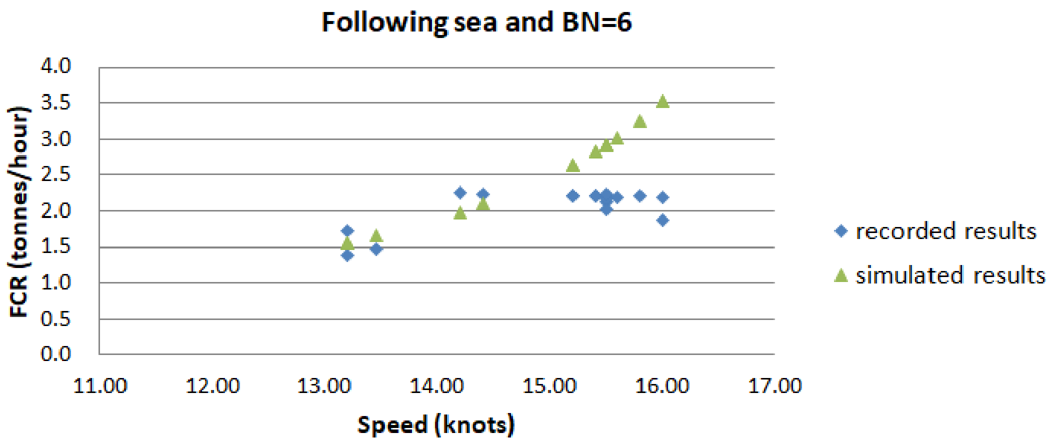


Figure 5.21 Validation results for following sea and BN = 6 (Laden Condition)

The difference between recorded and simulated FCR values under different weather conditions are listed in Table 5.2.

Table 5.2 Difference between recorded and simulated FCR values under different weather conditions

Weather and loading conditions	Head sea BN = 4* Ballast condition	Head sea BN = 5* Ballast condition	Head sea BN = 6 Ballast condition	Bow sea BN = 4* Ballast condition	Beam sea BN = 3* Laden Condition	Beam sea BN = 4* Laden Condition
Difference	-0.07%	9.33%	29.72%	0.83%	-3.74%	9.80%

Weather and loading conditions	Beam sea BN = 5 Laden Condition	Following sea BN = 3* Laden Condition	Following sea BN = 4* Laden Condition	Following sea BN = 5 Laden Condition	Following sea BN = 6 Laden Condition
Difference	12.33%	3.16%	10.21%	18.49%	28.15%

It can be seen from Figure 5.12 to Figure 5.22 and Table 5.2, the gaps between most of simulated results and recorded results are within acceptable range. For the weather and loading conditions with a star (*) tag in Table 5.2, their differences are relatively small, also the simulated results have a relatively good agreement with the recorded results for different speed. However, the other four conditions have bigger differences, which are conditions of head sea with BN 6 at Ballast condition, beam sea with BN 5 at Ballast condition and following sea with BN 5 and BN 6 at Laden condition. They show larger corresponding differences and also their two groups of results do not reach the agreement at each speed. In general, from the validation results, no matter what kinds of sailing directions or loading conditions the ship was sailing with, as long as BN is greater than or equal to 5, the validation results are not so good. Moreover, also when the ship speed exceeds 15 knots, the validation results are not good either. There are many reasons will cause these results. However, it can still be summarised that in this case study, when the ship was sailing under other most of common weather and loading conditions, especially with an average speed around 14 knots or even slower, the proposed approach can provide reliable simulated results to the users.

There are a number of reasons for the differences which are listed below:

First one is the uncertainties in the noon report. It can be observed from the noon report that sometimes when the ship sailed at same sea states and speeds, the noon report recorded several different FCR results. Also in the same weather conditions, the corresponding FCR did not increase as the speed increased. Even under different weather conditions, the FCR has not changed much for the same speed, and it has always maintained a flat trend. This can not be explained without further recorded data.

Besides, the recorded fuel consumption values of these repeated routes are also checked. It was found from the noon report that, sometimes the fuel consumption of the voyage at later time reduces suddenly, which becomes much less than the fuel consumption of the previous voyage even they have almost same average ship speed, weather and loading conditions. For those repeated voyages with long period between them, this may be due to there is dry-docking period between two voyages, which will reduce the effect of fouling or other time-dependent factors and help the ship save much fuel consumptions. In other words, these effects are not considered in the proposed system but was recorded in noon report. This will lead to some validation errors. For some other case studies, their sailing time is very close and it can be confirmed there is no dry-docking period between them, but the fuel consumption of later voyage still reduces a lot. This can not be explained without further information and can be regarded as another uncertainty in the noon report.

The weather conditions recorded in the noon report are the average values of BN and weather direction categories. The exact weather conditions encountered by the ship are unknown. This may also lead to the uncertainties in recorded results.

Another reason is the simplifications/assumptions with the model during the development of the system. The system does not take into account the trim condition during voyage as the actual trim conditions were not recorded. This may have a big impact on ship navigation as well as its energy efficiency especially in ballast condition. The slip is not included in the system, which may affect the propeller efficiency. The model also does not take the effects of currents into account.

Furthermore, while the ship's loading condition is recorded as Ballast or Laden, exact loading condition is not known, and this lead to uncertainties. All these above factors may cause the errors in the validation results.

However, overall, it can be seen from the validation results, most the simulated results have a good response to the weather condition and they perform a good trend with the speed increased.

The simulated total fuel consumption results for every single route are also checked with the recorded results. The comparison shows that for most routes, the difference between simulated fuel consumption and recorded fuel consumption is between -6% and 10%. From this view, it can also be regarded that the simulated results produced by the proposed system are consistent, reasonably accurate despite the uncertainties and the assumption. Therefore, the integrated methods in the weather routing tool, which provide accurate outcome trends and comparative analysis, will be able to help decision makers in shipping companies to identify the most optimum energy efficient voyage plan.

Next, according to the noon report, there is an actual recorded ocean crossing route whose departure point and destination point are given as 121°29'W \ 31°55'N and 144°21'E \ 34°34'N respectively, while the departure time is 2011-09-13, 19:00. The ocean crossing route has longer distance and the simulation for this route can show more clear benefits using global weather routing optimisation. However, before starting the optimisation, case studies following the exact same route, same departure time, same ETA and same speed plan still need to be carried out first to determine the accuracy of total brake power performance calculation with two different added wave resistance methods - one is based on numerical method and the other is based on modified Kwon's method. It should be highlighted that the recorded weather data in noon report are only average BN value for 24h period, and the specific weather data value is unknown in the weather range corresponding to a certain BN value. Therefore, four comprehensive case studies are executed, which are respectively:

A - Simulation with the maximum value in the weather range corresponding to every recorded BN while using numerical added wave resistance method;

B - Simulate with the average value in the weather range corresponding to every recorded BN while using numerical added wave resistance method;

C - Simulate with the minimum value in the weather range corresponding to every recorded BN while using numerical added wave resistance method;

D - Simulate with the recorded BN values based on modified Kwon's added wave resistance method;

Since the noon report only recorded the main engine fuel consumption rather than brake power, the fuel consumption results are used to represent the total power performance of the ship for comparison. The results of four case studies including fuel consumption on each stage and their corresponding weather data are listed in Table 5.3. And fuel consumption on each stage under different conditions is also drawn in Figure 5.23 for ease of observation.

Table 5.3 Results of verification case studies

	Noon report records					Case study A			Case study B			Case study C			Case study D
Stage	Sailing hours	Speed (knots)	Average BN	Direction	FC (tonnes)	Waves height (m)	Wind speeds (m/s)	FC (tonnes)	Waves height (m)	Wind speeds (m/s)	FC (tonnes)	Waves height (m)	Wind speeds (m/s)	FC (tonnes)	FC (tonnes)
1	24.00	12.50	4	Bow sea	36.60	2	7.9	36.55	1.5	6.7	34.99	1	5.5	32.84	35.99
2	25.00	12.60	3	Bow sea	40.80	1	5.4	33.55	0.75	4.4	33.07	0.5	3.4	32.94	35.33
3	24.00	12.90	3	Bow sea	36.80	1	5.4	34.44	0.75	4.4	33.93	0.5	3.4	33.81	35.74
4	25.00	12.60	4	Head sea	37.50	2	7.9	39.38	1.5	6.7	37.37	1	5.5	33.94	37.45
5	24.00	12.30	4	Head sea	36.90	2	7.9	35.38	1.5	6.7	33.55	1	5.5	30.51	34.14
6	25.00	11.90	6	Head sea	42.30	4	13.8	50.17	3.5	12.3	44.29	3	10.8	38.16	39.17
7	24.00	11.10	6	Head sea	42.60	4	13.8	39.86	3.5	12.3	35.37	3	10.8	30.50	32.44
8	25.00	11.70	6	Head sea	45.20	4	13.8	47.27	3.5	12.3	41.84	3	10.8	36.07	37.45
9	24.00	11.90	6	Head sea	44.00	4	13.8	47.58	3.5	12.3	42.04	3	10.8	36.24	37.19
10	25.00	12.80	4	Head sea	38.20	2	7.9	41.15	1.5	6.7	39.08	1	5.5	35.49	38.79
11	24.00	12.10	4	Head sea	36.60	2	7.9	33.95	1.5	6.7	32.21	1	5.5	29.31	32.86
12	25.00	12.80	4	Bow sea	45.50	2	7.9	38.66	1.5	6.7	37.03	1	5.5	34.75	37.57
13	24.00	12.30	4	Head sea	36.50	2	7.9	35.50	1.5	6.7	33.67	1	5.5	30.61	34.14
14	25.00	10.40	5	Head sea	33.50	3	10.7	28.87	2.5	9.35	26.33	2	8	22.96	25.99
15	24.00	10.50	7	Bow sea	36.20	5.5	17.1	41.23	4.75	15.5	32.27	4	13.9	28.65	31.84
16	25.00	9.90	6	Bow sea	34.10	4	13.8	26.77	3.5	12.3	23.87	3	10.8	21.29	23.16
Total FC (tonnes)			623.30				610.32			560.91			508.06		549.24

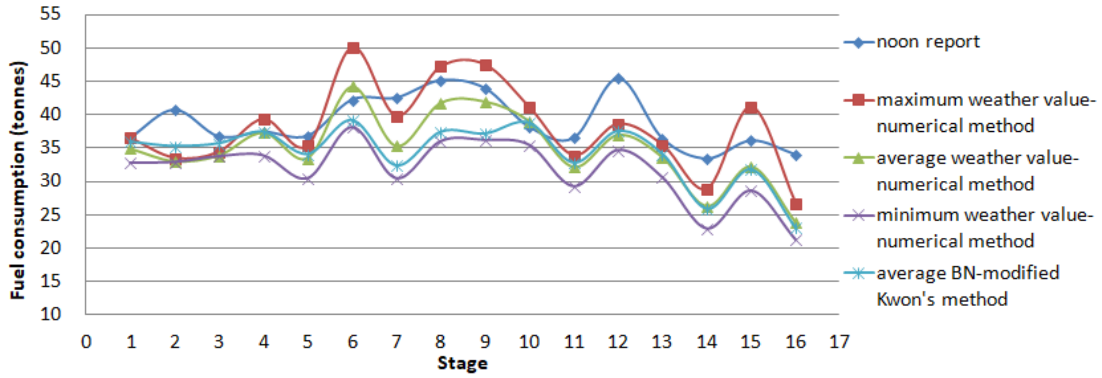


Figure 5.22 Fuel consumption at each stage under different conditions

As can be seen from Table 5.3 and Figure 5.23, for most stages, the simulated fuel consumption is less than the recorded fuel consumption. For case studies B and D, which are calculated based on average weather data, their difference are respectively 10.00% less and 11.89% less compared to recorded information. Only for several stages in maximum weather conditions and calculated based on numerical method, the simulated fuel consumption is average 10.44% more than recorded fuel consumption. From total fuel consumption perspective, according to the weather conditions recorded in the noon report, the possible maximum fuel consumption and minimum fuel consumption predicted by the system are 610.32 tonnes and 508.06 tonne respectively, which is still less than the recorded value of 623.3 tonnes. Again, several reasons mentioned above may cause the recorded fuel consumption values larger than simulated results. Besides, this is a single route and there are no more same routes in the noon report to refer to, so the recorded results may also be somewhat accidental. These inconsistencies may come from various sources such the ship performing special operations during the voyage, or the crew did not record the data accurately.

For Instance, the Stage 7 has lower speed and less sailing hours but has more fuel consumption than Stage 6 despite the weather conditions on Stage 6 and Stage 7 are exactly the same.

It can be concluded that the trends of the simulated results are generally similar to those of the noon report, while the trends of all simulated results are very consistent and the simulated results have a better response to the weather condition and speed changes. It can be seen that:

1. When BN is larger than or equal to 6, the results produced by the numerical method under different weather conditions (maximum, average, minimum values) have a big difference and when BN is below 6, the results do not differ much. The reason is that in the wind scale, the larger the BN, the greater the range of weather conditions it represents. For example, when BN is 6, the wind speed can change from 10.8 m/s to 13.8 m/s which is 3m/s difference, but when BN is 3, the wind speed can only change from 3.4 m/s to 5.4 m/s, which only has 2m/s difference. Therefore, the larger the BN, the greater the range of weather conditions it represents and the bigger difference between the results of the maximum and minimum weather conditions represented by this BN.

2. When BN is less than 6, the results produced by modified Kwon's method is in good agreement with the results produced by numerical method under average weather condition. This shows the modified Kwon's method also reflects the brake power performance under average weather condition. It also proves both numerical method and the modified Kwon's method can perform well when BN is less than 6.

3. When BN is larger than or equal to 6, the fuel consumption values produced by modified Kwon's method are smaller than the values produced by numerical method under average weather condition, especially on Stage 6 to Stage 9. This shows the modified Kwon's method does not perform very well at the condition of BN exceeds 6. This means the numerical method is a very good supplement for the modified Kwon's method.

All of the above results show that both methods can calculate reasonable brake power performance. When BN is less than 6, the modified Kwon's method which is easy to operate, which does not require the hull form data, is a good choice. When BN is greater than 6, it is better to use the numerical method, although its operation is a little complicated as the hull form data is required and a set of runs need to be performed for range of frequencies as well as extra calculations for various weather conditions.

It was also found that the recorded weather data in noon report often differs from the weather data extracted from the database. So in order to compare with the recorded information more reasonably, a case study E - following the exact same route, same departure time, same ETA and same speed plan, but based on the weather data extracted from the historical database is executed. The fuel consumption results are produced based on the numerical method, which are listed in Table 5.4. Here, the information of case study B including the weather data recorded in noon report and fuel consumption results based on the average recorded weather data value using same numerical method are also listed in Table 5.4 for comparison purposes. It should be noted that the weather data extracted from the database are exact values like 5.0 m/s of wind speed or 25 degrees of wave direction, rather than average weather conditions as given in noon reports. To facilitate comparison, all these weather data are respectively converted to BN and encountered wave direction categories in Table 5.4.

Table 5.4 Results based on different weather sources

	Weather data given in noon report Case study B				Weather data extracted from historical weather database Case study E		
Stage	Speed (knots)	Average BN	Direction	FC (tonnes)	Average BN	Direction	FC (tonnes)
1	12.50	4	Bow sea	34.99	4	Head sea	39.65
2	12.60	3	Bow sea	33.07	5	Bow sea	39.48
3	12.90	3	Bow sea	33.93	4	Bow sea	39.37
4	12.60	4	Head sea	37.37	4	Head sea	34.30
5	12.30	4	Head sea	33.55	4	Head sea	35.67
6	11.90	6	Head sea	44.29	4	Head sea	33.66
7	11.10	6	Head sea	35.37	5	Head sea	34.53
8	11.70	6	Head sea	41.84	6	Bow sea	40.77
9	11.90	6	Head sea	42.04	5	Head sea	38.86
10	12.80	4	Head sea	39.08	5	Bow sea	41.98
11	12.10	4	Head sea	32.21	4	Head sea	29.21
12	12.80	4	Bow sea	37.03	4	Head sea	41.88
13	12.30	4	Head sea	33.67	4	Beam sea	31.81
14	10.40	5	Head sea	26.33	4	Following sea	19.58
15	10.50	7	Bow sea	32.27	5	Head sea	23.01
16	9.90	6	Bow sea	23.87	6	Beam sea	22.61
Average BN of the whole voyage			4.75			4.56	
Total FC (tonnes)			560.91			546.38	

As can be seen from Table 5.4, both results are obtained using the same numerical method, but correspond to different weather sources. The total fuel consumption value based on the weather conditions from historical weather database is a little smaller than that based on the weather conditions recorded in the noon report. This is because the weather conditions from two sources are different. In this case study, compared to recorded weather data in noon report, the weather data extracted from historical weather database has lower average BN and less head sea and bow sea directions, so that it will produce less fuel consumption. However, no matter what kind of source the weather conditions come from, the proposed system can have a good response to it. This also highlights some of the uncertainties about the recorded weather data in noon report.

Therefore, there is a strong reason to believe that the proposed system can produce accurate results for users.

Next, the global weather routing optimisation is carried out based on the proposed weather routing system. The grids system has 17 stages, and except the first and last stage, each stage has maximum 15 waypoints with equal distance of 60 nautical miles. The grids system for this case study can be seen in Figure 5.3. Ship speed ranges from minimum 9.5 knots to 15.8 knots with the interval speed 0.1 knot. The weather routing optimisation Pareto front results are shown in Figure 5.24.

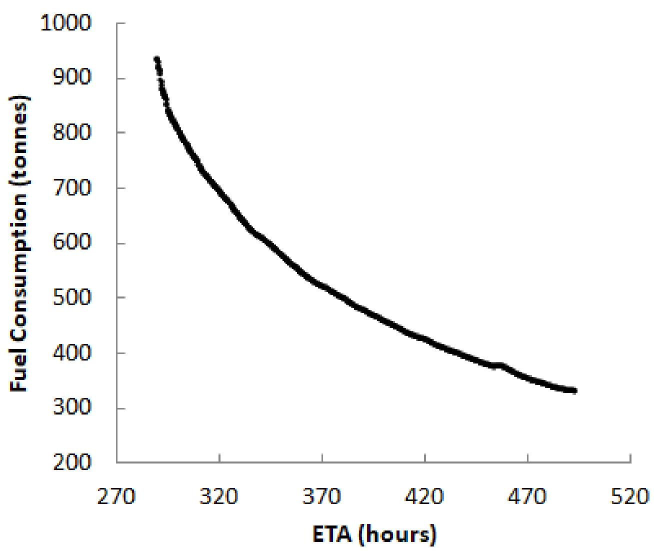


Figure 5.23 Pareto front of case study

It can be seen from Figure 5.23, that there are almost 2000 potential route plans during this voyage. The ETA ranges from 289.6 h to 493.1 h, while the fuel consumption ranges from 331.75 tonnes to 937.91 tonnes. Speed sets, ETA and fuel consumption of four typical routes: Noon report recorded route, 392h ETA route, Minimum fuel consumption route and Minimum ETA route are listed in Table 5.5. The weather conditions on each stage of 392 h ETA route are also listed to see the effect of global optimisation. Here, because the global weather routing optimisation is executed based on the weather data extracted from the historical weather database, the fuel consumption value of noon report adopts the fuel consumption value of case study E for the aim of comparison.

According to the revised noon report, the recorded route has 392 h of ETA and 546.38 tonnes of fuel consumption. For the sake of comparison, the potential route with the same ETA is selected. Although their average speed is quite similar: 11.89 knots and 12.14 knots, their speed sets have different changing trends: the recorded speed sets have lower speeds on middle stages, while the global optimised speed sets shows the trend of lower speed - higher speed - lower speed - higher speed during the voyage. It can also be seen from the weather conditions of the optimised route, the global weather routing optimisation can make the ship sail under relatively weaker wind conditions (average BN is 3.63, while that of the recorded route is 4.56) and more favourable wave directions (more beam sea and following sea conditions). However, in the aspect of fuel consumption, which is the most important energy efficiency indicator, the route calculated in this system has 475.60 tonnes of fuel consumption, which means the global weather routing optimisation can make the ship consume 12.95% less fuel than the recorded route. This proves the system can provide a much better voyage plan towards energy efficiency for the shipmasters.

Besides, from the final Pareto front, both minimum fuel consumption route and minimum ETA route can be extracted. For the former route, it has 493.1 h of ETA and 331.75 tonnes of fuel consumption with almost slowest average speed 9.66 knots; while for the latter route, it has 289.6 h of ETA and 937.91 tonnes of fuel consumption, but with fastest average speed 15.8 knots. This shows that for this route, when sailing time is reduced by nearly 200 hours (41.27%), fuel consumption will increase by 606.16 tons, which is an increase of nearly 182.72%! Therefore, the operator can use this result as a reference to determine the appropriate navigation plan without violating the chartering contract.

Table 5.5 Total results of Aframax oil tanker case study

Stage	Noon report recorded route	392h ETA route			Minimum fuel consumption route	Minimum ETA route
	Speed (knots)	BN	Direction	Speed (knots)	Speed (knots)	Speed (knots)
1	12.5	4	Bow Sea	11.7	9.5	15.8
2	12.6	5	Beam sea	11.3	9.5	15.8
3	12.9	3	Bow Sea	11.8	9.5	15.8
4	12.6	3	Beam sea	12.5	10	15.8
5	12.3	3	Beam sea	12.6	10.2	15.8
6	11.9	3	Beam sea	12	9.5	15.8
7	11.1	4	Head sea	10.3	9.5	15.8
8	11.7	4	Head sea	10.4	9.5	15.8
9	11.9	5	Beam sea	12.2	9.5	15.8
10	12.8	4	Beam sea	12.6	9.6	15.8
11	12.1	4	Following sea	12.9	9.9	15.8
12	12.8	3	Following sea	12.9	10.2	15.8
13	12.3	1	Beam sea	13.1	9.6	15.8
14	10.4	3	Beam sea	12.6	9.5	15.8
15	10.5	4	Beam sea	12.9	9.5	15.8
16	9.9	5	Following sea	12.4	9.5	15.8
ETA (hours)	392.0		392.0		493.1	289.6
FC (tonnes)	546.38		475.60		331.75	937.91

Furthermore, the internal results related to ship safety are also extracted to prove the effectiveness of ship safety module. According to the selected ship safety criterion (See Section 4.5), the limit values of four seakeeping performance of this model ship are determined: the probability of slamming is 0.017, the probability of deck wetness is 0.05, RMS of roll is 6 deg and RMS of vertical acceleration at FP is 1.258.

Among them, the limit values of probability of slamming and RMS of vertical acceleration at FP are calculated based on the linear relationship between the corresponding value and ship length (See Table 4.11).

All the four ship safety performance of each stage for 392h ETA route, minimum fuel consumption route and minimum ETA route are respectively listed in Table 5.6, Table 5.7 and Table 5.8.

As can be seen from Table 5.6, Table 5.7 and Table 5.8, all the ship safety performance values are less than the corresponding reference value, so it can be concluded that all the voyage plans meet the ship safety criterion. Even the minimum ETA route, which is also the fastest route, is safe enough. This can prove the ship safety module works well.

Table 5.6 Ship safety test for 392h ETA route

Stage	Speed	Probability of slamming	Probability of deck wetness	RMS of roll	RMS of vertical acceleration at FP
1	11.7	0.000	0.000	0.081	0.375
2	11.3	0.000	0.000	0.207	0.601
3	11.8	0.000	0.000	0.300	0.380
4	12.5	0.000	0.000	0.414	0.348
5	12.6	0.000	0.000	0.359	0.301
6	12	0.000	0.000	0.072	0.335
7	10.3	0.000	0.000	0.493	0.543
8	10.4	0.000	0.000	0.292	0.580
9	12.2	0.000	0.000	0.802	0.676
10	12.6	0.000	0.000	0.583	0.571
11	12.9	0.000	0.000	0.234	0.374
12	12.9	0.000	0.000	0.354	0.389
13	13.1	0.000	0.000	0.193	0.468
14	12.6	0.000	0.000	0.000	0.436
15	12.9	0.000	0.000	0.147	0.746
16	12.4	0.000	0.000	0.018	0.872
Reference safe value		0.017	0.05	6	1.258

Table 5.7 Ship safety test for minimum fuel consumption route

Stage	Speed	Probability of slamming	Probability of deck wetness	RMS of roll	RMS of vertical acceleration at FP
1	9.5	0.000	0.000	0.288	0.377
2	9.5	0.000	0.000	0.615	0.653
3	9.5	0.000	0.000	0.164	0.328
4	10	0.000	0.000	0.156	0.313
5	10.2	0.000	0.000	0.235	0.303
6	9.5	0.000	0.000	0.178	0.557
7	9.5	0.000	0.000	0.531	0.587
8	9.5	0.000	0.000	0.648	0.710
9	9.5	0.000	0.000	0.456	0.498
10	9.6	0.000	0.000	0.130	0.411
11	9.9	0.000	0.000	0.435	0.663
12	10.2	0.000	0.000	0.000	0.711
13	9.6	0.000	0.000	0.010	0.587
14	9.5	0.000	0.000	0.676	0.964
15	9.5	0.000	0.000	0.231	0.773
16	9.5	0.000	0.000	0.182	0.650
Reference safe value		0.017	0.05	6	1.258

Table 5.8 Ship safety test for minimum ETA route

Stage	Speed	Probability of slamming	Probability of deck wetness	RMS of roll	RMS of vertical acceleration at FP
1	15.8	0.000	0.000	0.128	0.379
2	15.8	0.000	0.000	0.234	0.582
3	15.8	0.000	0.000	0.288	0.475
4	15.8	0.000	0.000	0.225	0.327
5	15.8	0.000	0.000	0.000	0.442
6	15.8	0.000	0.000	0.494	0.819
7	15.8	0.000	0.000	0.155	0.466
8	15.8	0.000	0.000	0.661	0.993
9	15.8	0.000	0.000	0.445	0.909
10	15.8	0.000	0.000	0.337	0.716
11	15.8	0.000	0.000	0.442	0.784
12	15.8	0.000	0.000	0.000	0.516
13	15.8	0.000	0.000	0.323	0.732
14	15.8	0.000	0.000	0.570	0.796
15	15.8	0.000	0.000	0.624	0.680
16	15.8	0.000	0.000	0.008	0.527
Reference safe value		0.017	0.05	6	1.258

Based on all above, it can prove that this system can provide more optimal route plan suggestions for the shipmasters and it has a certain practical significance.

Four typical routes extracted from post-processing module are all drawn in Figure 5.25. It can be seen from Figure 5.25, the optimised route under 392 hours of ETA is different than the recorded route. The minimum ETA route coincides with the great circle, because the ship that pursues the fastest route not only adopts the highest speed during the voyage, but also sails along the shortest route.

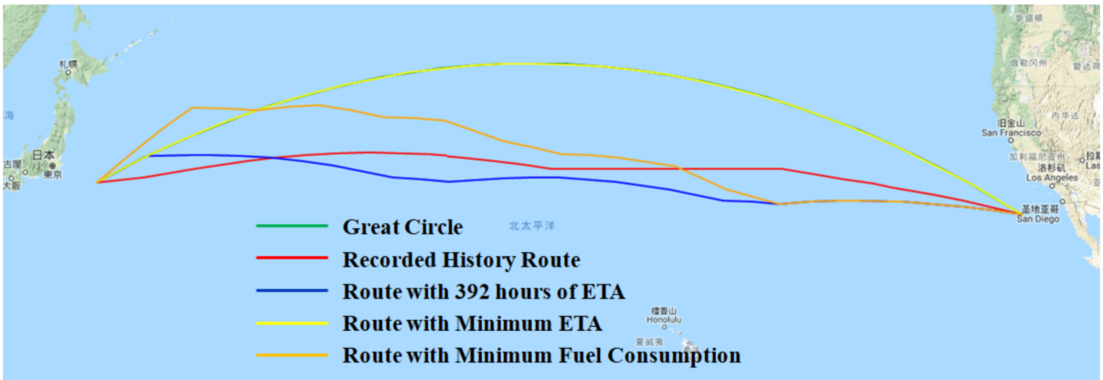


Figure 5.24 Optimal routes based on different requirements(Map data ©2016 Google)

5.4 Conclusion

This chapter introduces the core content of this study: ship weather routing system towards energy efficiency. The operation of each module in the system and the data transmission relationship between among them are elaborated. The files reading function is a prerequisite for the operation of each module, which is responsible for reading or decoding the data or files required by each module. In the ship performance calculation module, the calculation process for fuel consumption is described in detail. In the grids system design module, the basic grid system design principle is introduced, and then a land avoidance function that satisfies the vast majority of navigation conditions is developed. The role and operation of weather data module and ship safety module are also introduced. In the weather routing module, a global and local optimisation strategy is introduced to calculate the optimal voyage plan under different ETA requirements. In the post-processing module, a backward iteration method is introduced to extract the information of the navigation plan of the minimum fuel consumption under the target ETA, and a Google Maps based route display tool is introduced to visualise the route on the map.

The input condition of the entire system is only the ship's particulars and navigation plan. The output is a voyage plan of the minimum fuel consumption under target ETA, including ship headings and speed at each stage. Finally, several case studies based on a 115K DWT Crude Oil Tanker sailing along different real routes are carried out to preliminarily verify the accuracy and effectiveness of the weather routing system. With these case studies, the ship brake power performance in calm water, the FCR performance in various weather and speed conditions, the fuel consumption performance response to the weather conditions and ship speeds based on numerical method and modified Kwon's method, the difference of weather data from different sources, the effects of global optimisation on fuel saving and ship operational plans, the safety on each stage of the voyage etc. are all validated. The validation procedure proves all the integrated modules work well. The results show the proposed system can provide users a very useful platform to develop ship operational strategy towards high energy efficiency.

6 Effective Methods for Improving Working Efficiency of the Ship Weather Routing System

6.1 Introduction

In the last chapter, a ship weather routing system for energy efficient shipping is introduced in detail. This system is composed of several modules, including grids system design module, weather routing module, ship safety module, etc. Every module has its own task, and every one of them should cooperate with each other so that the whole system can run well towards to a shipping mission. However, the working efficiency of this relatively complicated system is not high enough. For one simple case, it always takes a number of hours to complete the calculation, which cannot meet the practical demands. Therefore, several methods for improving the working efficiency of this system are designed. These methods include not only change of running logic of the system, but also the optimisation of programming codes.

6.2 Effective methods to upgrade the system

When the ship weather routing system was first developed, due to the complicated relationship among these modules and vast amount of calculations, the working efficiency was very low. Therefore, several effective methods are designed as explained below to enhance the working efficiency of this system.

6.2.1 Creating ship performance database

In the ship performance calculation module, the calculation is carried out every time when the ship arrives a new waypoint and is assigned with new speed or direction or given new weather data. The constant introduction of so many new conditions will lead to more and more calculations. This process costs much computing resources and is certainly very time-consuming.

To obtain ship performance very quickly and conveniently, a Ship Performance Profile File (SPP), which is developed in 2015 by Strathclyde University SCC project research group including the author of this thesis, is generated (Howett, 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, 2015). The file format uses the netCDF (NETwork Common Data Form) specification, a self-describing, machine-independent file format intended for string multidimensional scientific data.

One typical file contains these dimensions: speed, significant wave height, relative wave angle, true wind speed, true wind angle and an output attribute: brake power, which can be clearly seen in Table 6.1. The variable name refers to the name appears in the weather routing system program.

Table 6.1 Dimension and attribute variables of a typical file

Dimension/Attribute	Variable Name	Unit
Speed	platform_speed_wrt_ground	m/s
Significant Wave Height	sea_surface_wave_significant_height	m
Relative Wave Angle	sea_surface_wave_from_direction_wrt_platform	degree
True Wind Speed	wind_speed	m/s
True Wind Angle	wind_from_direction_wrt_platform	degree
Power	power_main_engine	kW

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:

$$FC = P_B \cdot sfoc \cdot t \tag{6.1}$$

Where, the difference between formula 6.1 and 5.4 is that P_B in formula 6.1 is brake power obtained by ship performance profile. The other variables are same, FC is fuel consumption, *sfoc* (g/kWh) is specific fuel oil consumption of the engine, t is the duration of ship navigation.

Here, a five-dimensional linear interpolation method is introduced, which is also developed by SCC project research group. Its principle is based on the previous two-dimensional linear interpolation, which extends two dimensions to five dimensions. Its interpolation accuracy is also very good and can meet the calculation requirements.

Besides, the ship performance profile may also include additional dimensions (e.g. draft/loading condition) or additional attributes (e.g. fuel consumption) where required. So when a new calculation condition is assigned to the system, or when the user needs to calculate different attributes, a new ship performance file can be generated. Or when alternative energy saving devices or technologies are taken into account, the user only needs to generate a new ship performance profile file according to the device or technology performance calculation method. The process of generating a new file does not significantly affect the required reading and writing code, nor does it impair compatibility with the system and existing files. This makes the ship weather routing system combine with other technologies well.

The files reading function is also designed to be compatible with the netCDF format, ensuring that the ship performance file can be well read in the system. As an illustration, the energy saving effect of Flettner rotor technology, one of wind assisted technologies for shipping, is predicted based on this weather routing system in Chapter 8.

6.2.2 Redefining ship travel principle and adjusting the grids system scale

The layout of the Grids system has been introduced in Section 5.2.2. After the grids system is fixed, travel directions should be determined from every departure point to arrival point. Obviously, in the original grids system, if the ship can travel from each waypoint to every waypoint in the next stage, it is unrealistic and the amount of calculation is also very large. It can be imagined that some special circumstances will make the angle of the ship's course adjustment very extreme. For example, the route may have a distinct zigzag shape under some extreme shipping conditions which is unreasonable.

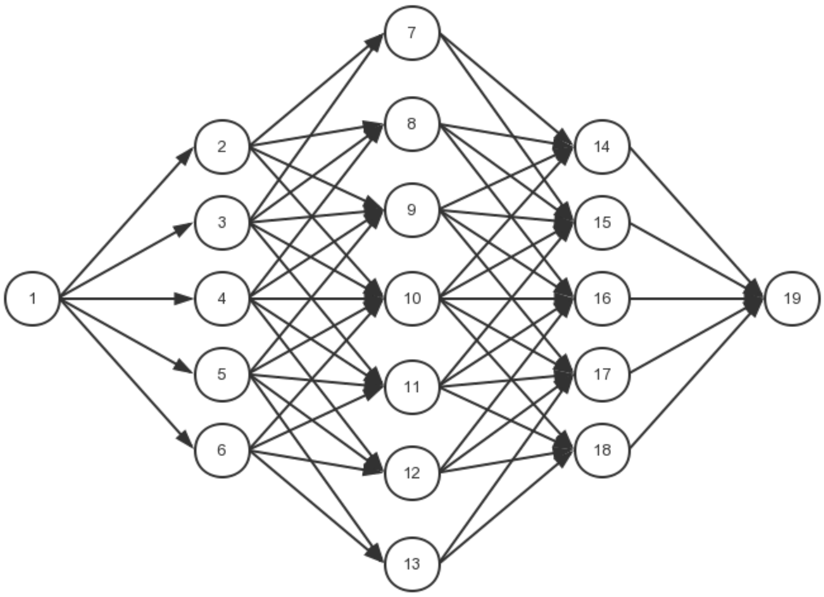
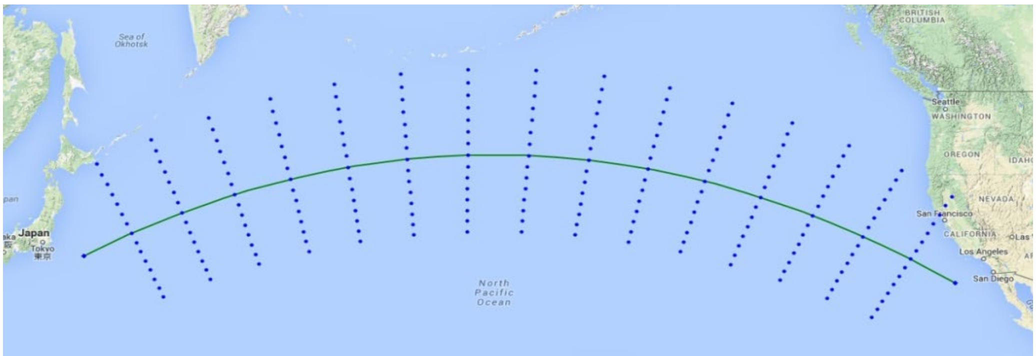
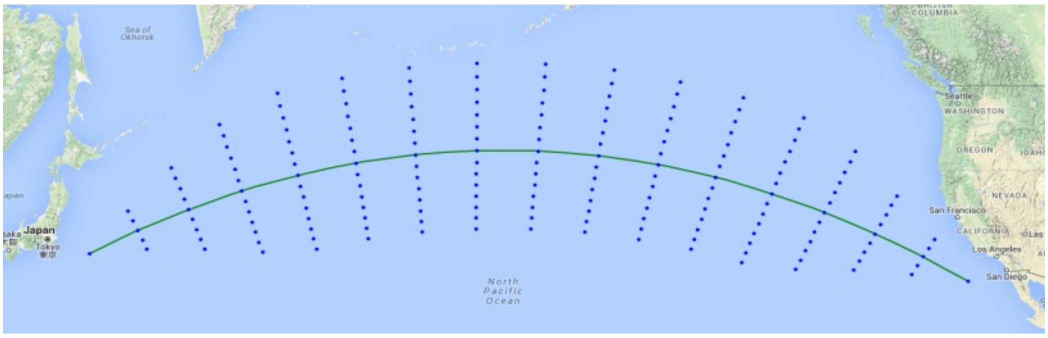


Figure 6.1 Ship routing network

Considering the larger course deviations are not feasible and would be unrealistic for an optimum route, it is reasonable for the system to set the ship to sail from one waypoint to the next stage in only five directions. So that, from departure point, except waypoints near the grids system border, a ship at every waypoint can sail to the next five adjacent potential waypoints, which can be seen in Figure 6.1. When these nodes are connected, many potential route segments are formed. This also means some redundant waypoints at both ends of the route where the ship will not pass can be deleted in grids system. Compared with Figure 6.2 (a), new grids system with same waypoints resolution can be seen in Figure 6.2 (b). This also answers the question raised in Figure 5.6 that why the number of waypoints on each stage is gradually changed.



(a) Original grids system



(b) Redefined grids system

Figure 6.2 Comparison of grids system before and after upgrade (Map data ©2017 Google)

Besides, the number of stages, the number of vertical waypoints and their vertical distance in one stage are all set to be adjustable. For some simple cases like wide open water and steady sea states, the number of stages or the number of vertical waypoints can be reduced, which means when the shipping area is not very complicated, the grids, to some degree, can adopt lower waypoint resolution to reduce the calculation amount.

Taking the actual route as an example, the ship departs from Singapore and needs to drive out of the Straits of Malacca, then bypass Madagascar Island and finally arrive at Beira in eastern Mozambique. The grids system designed for this actual route is shown in Figure 6.3.

According to geographical information, the entire route can be divided into three parts.

The first part: The ship needs to pass through the relatively narrow Straits of Malacca. It needs to arrange more dense waypoints to enhance the accuracy of the ship's driving and ensure that the ship can sail out of the Straits through these waypoints.

The second part: The ship sails in wide open water in Indian Ocean. For this case, the waypoint density can be appropriately relaxed. The distance between every two stages can be expanded and the number of stages is reduced. When reducing the density of waypoints, it is necessary to consider the effect of the weather change. In a certain period of time and a certain area, if the weather changes in a steady manner, the waypoint density can be appropriately reduced. If the weather conditions are more complicated, lowering the waypoint density excessively will make the ship operation insensitive to weather factors, which will result in inaccurate final results.

The third part: The Ship needs to bypass Madagascar Island and enter the Mozambique Channel. The density of waypoints needs to be increased again, but it does not need to be as dense as the first stage, as the Mozambique Channel is not as narrow as the Strait of Malacca.

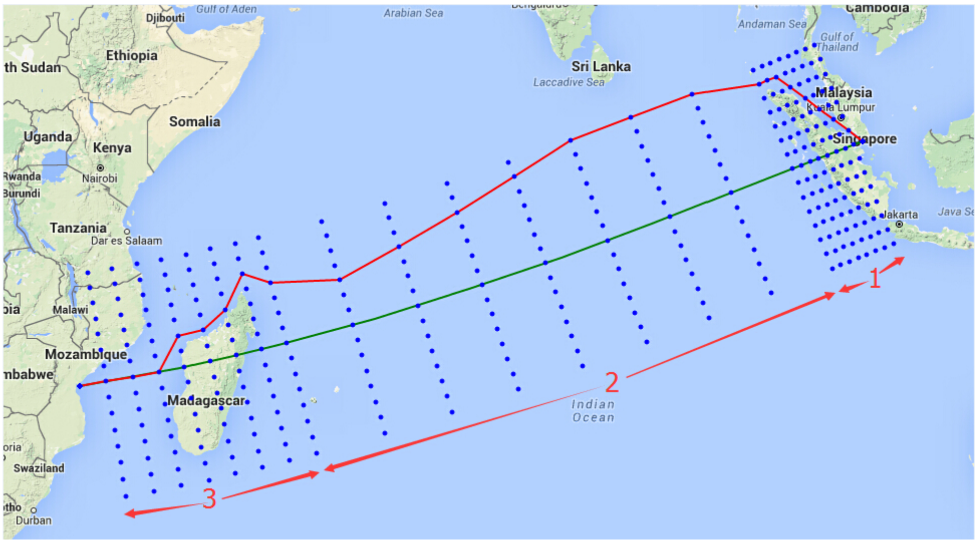


Figure 6.3 Grids system designed for an actual route (Map data ©2017 Google)

6.2.3 Integrating ship safety module into ship performance prediction module

In the origin ship safety module, the safety test will be carried out on every potential route calculation, which leads to huge calculation effort. As the ship performance database, which covers all possible sea states the ship may meet, is introduced, it will be reasonable to merge the ship safety module with the ship performance database, as can be shown in Figure 6.4.

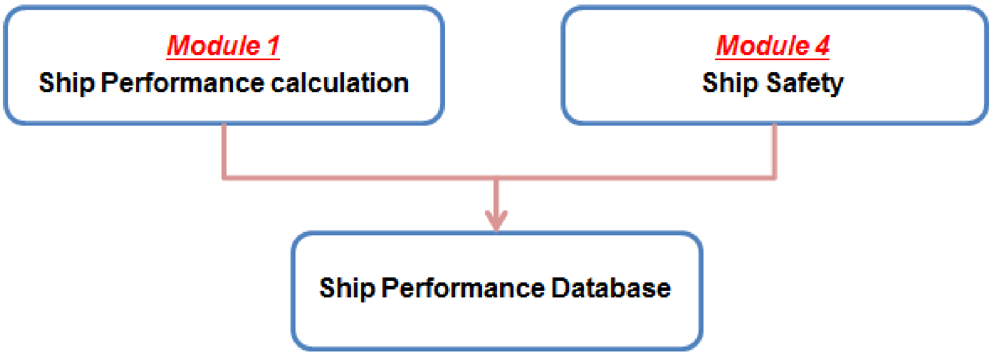


Figure 6.4 Merge two modules to ship performance database

This means, when the typical ship performance database introduced in Section 6.2.1, then the ship safety test is introduced at the same time. The combined condition naturally will result in some changes in the value of brake power calculated. If the brake power value, which is calculated through 5-D interpolation is 'NaN' that means it is unfavorable for ships to pass through a certain area with a certain speed under the certain weather condition. The ship will not adopt this operation to pass through this sea area at this particular time. It means the system will stop calculating the result for this particular area.

If the brake power value is a reasonable numerical value rather than 'NaN', which means the ship can select suitable speed (relates to suitable engine power) to guarantee the safe ship passage in the certain sea states. In other words, all brake power with the numerical value obtained from the ship performance database can ensure that the shipping in that condition is absolutely safe. These corresponding results will be saved and will be used for the voyage optimisation. This method not only shortens the calculation time a lot but also makes the structure of system much simpler.

6.2.4 Deleting the results in every waypoint which cannot meet the time schedule

This method can be also regarded as setting duration constraint in every waypoint. For a certain waypoint, it may save many potential results, but not all of these results can reach destination point within the required ETA. For example, if the arrival time at this waypoint is too late, even the ship travels with maximum speed in next stages, it still cannot reach the destination in time. Or if the arrival time at this waypoint is very early, even the ship travels with minimum speed in next stages, it will reach the destination in advance. Here, it is assumed that the ship cannot stop, it must travel with the speed between minimum speed and maximum speed. So some results which cannot meet the ETA requirement should be deleted.

Several time boundaries for a waypoint are defined as below (Shao, 2013):

$$t_{down1} = D_{departure} / V_{\max} \tag{6.2}$$

$$t_{up1} = 1.5 D_{departure} / V_{\min} \tag{6.3}$$

$$t_{down2} = t_{end} - t_r / 2 - 1.5 D_{destination} / V_{\min} \tag{6.4}$$

$$t_{up2} = t_{end} + t_r / 2 - D_{destination} / V_{\max} \tag{6.5}$$

Where t_{down1} and t_{up1} are time boundaries from the view of $D_{departure}$, and $D_{departure}$ is the distance of great circle from the departure point to this point; while t_{down2}, t_{up2} are time boundaries from the view of $D_{destination}$, and $D_{destination}$ is the distance of great circle from this point to the destination point; t_{end} is the specified arrival time and t_r is the interesting time range around t_{end}; $V_{\min}$ and $V_{\max}$ are minimum speed and maximum speed respectively. Here, 1.5 times of distance is large enough to overcome the use of bigger minimum speed instead of the minimum ship speed over the voyage. These limiting values/relations can also be adjusted according to actual needs.

Based on above, the final available time range (t_{down}, t_{up}) for a waypoint can be expressed as:

$$t_{down} = Max(t_{down1}, t_{down2}) \tag{6.6}$$

$$t_{up} = Min(t_{up1}, t_{up2}) \tag{6.7}$$

Therefore, after deleting these redundant results which are out of the scope defined above, the calculation time will be reduced considerably.

6.2.5 Setting the speed control parameter

In the initial voyage optimisation process, the system will take into account all speed options varying from minimum speed to maximum speed. However, most speed options will not affect the final optimum result actually. More attention is paid to a range around the average speed ($V_{average}$), which can be easily estimated by

$$V_{average} = D_{GC} / ETA \tag{6.8}$$

Where, D_{GC} is the distance of great circle.

Here, a speed control parameter can be introduced. This parameter is used to set a reasonable range of change for the ship speed at each stage. In this system, the ship needs to navigate towards the next stage based on initial information stored on a waypoint, where speed is an important attribute in this initial information. The ship operators can make a plan for the speed of the next stage by referring to the speed value of this initial information. The parameter used to plan the speed is the speed control parameter. For example, this parameter is set at 3 knots but can be changed depending on the route. This means from every departure point, the speed options for the ship travels to next stage will concentrate upon the range of average speed ±3 knots. The same principle is also applied to other waypoints. The ship will travel to the next stage within the available speed range based on its corresponding speed value saved in the current waypoint.

This method can not only save the calculation time but also make the ship sails more stable during the whole shipping voyage as there are practical limits with regards to engine loading. When encountering bad weather during the voyage, the ship may need to accelerate or decelerate significantly. At this time, the speed control parameter can be linked to the weather forecast and appropriately increased, thus, the range of speed options to be calculated by the system is expanded, so that the weather routing system can calculate the optimal voyage plan for the users.

6.2.6 Deleting the results in every waypoint which cannot meet expected fuel consumption

This method is similar to method 6.2.4. The idea of this method is to make an estimation of the total fuel consumption of the ship over the entire voyage based on the ship's navigation information at the time when the ship passes each waypoint. By comparison of this estimated total fuel consumption and the total fuel consumption that the user expects before the ship departure, those results that are far exceeding expectations or extremely unreasonable are removed. This is to set a constraint on the estimated total fuel consumption at each stage of the ship's navigation. The specific approach is introduced as below.

According to the weather data in departure port, together with the estimated average speed and ETA, the initial estimated total fuel consumption can be easily obtained. Next, when the ship reaches one waypoint, the fuel consumption value of passed route will be saved in this waypoint. With the same method, according to the weather data in this waypoint, together with the rest of great circle distance and ETA, the estimated fuel consumption for the rest of journey can be determined. Here, a fuel consumption control parameter is introduced as well. If the sum of current fuel consumption and the rest of fuel consumption, thus the estimated total fuel consumption at the current situation, is bigger than the value of initial estimated total fuel consumption multiplied by fuel consumption control parameter, this corresponding result will be deleted. Based on many case studies, the empirical fuel consumption control parameter can be set as 1.5. This method is also applied in every waypoint to reduce the calculation amount.

6.2.7 Optimisation of programming codes

In the beginning, the whole system was developed in Matlab. If users also select hydrodynamic software to calculate the ship performance, then overall framework is shown in Figure 6.5. The figure clearly shows the input and output relationships of the data and also shows the various functions that the system needs to calculate the optimal voyage plan. It is well known that Matlab is to some degree a library of generic codes, that there are many existing functions can be used directly. However, the calculation efficiency of Matlab is still very low, especially for the case with the large amount of calculation. At this time another programming language C# could be considered. C# language needs to re-structure most of the functions, like interpolation functions, decoding functions, various geography functions including distances, angle functions, etc. The programming with C# is very big task and difficult especially for beginners, but C# can greatly improve calculation efficiency of the system, and it can also provide interfaces for some program modules developed in other languages.

So that C# language is selected to replace Matlab. In C# programming process, not only the codes are well converted from Matlab, but also the structure of the code is well optimised. Besides, C# language also provides a very powerful parallel running pattern, For example, when the ship sails from a waypoint to the five waypoints at the next stage, the calculation of each direction can be performed simultaneously by using the parallel pattern. This is really helpful to increase the working efficiency of the system.

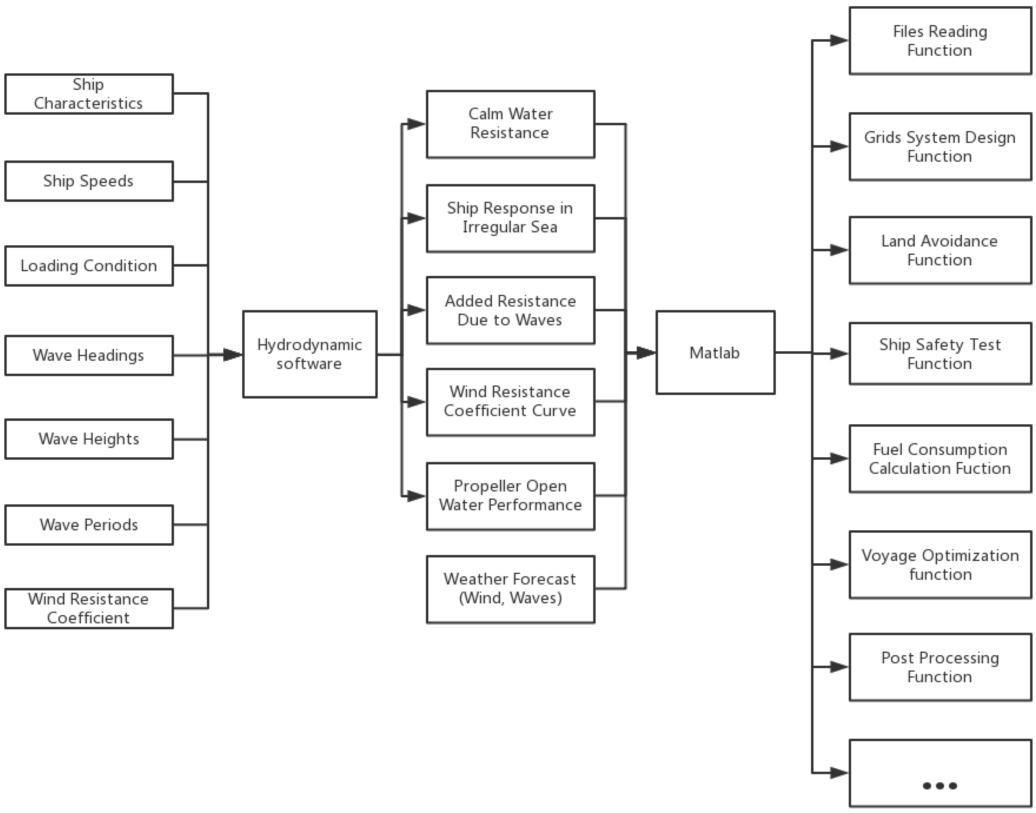


Figure 6.5 Structure of weather routing system based on hydrodynamic software and Matlab

6.3 Case Study

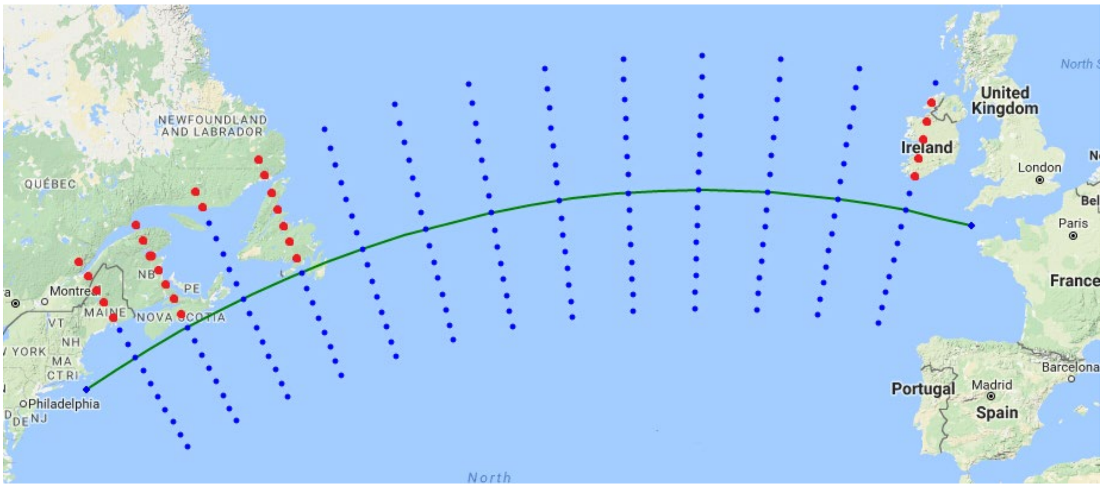
A case study is carried out in order to demonstrate the validity of these methods. A 35,500DWT Bulk Carrier is taken as the ship model in the case study. The main particulars of the ship, main engine and propeller are given in Table 6.2.

Table 6.2 Main particulars of 35,500DWT Bulk Carrier

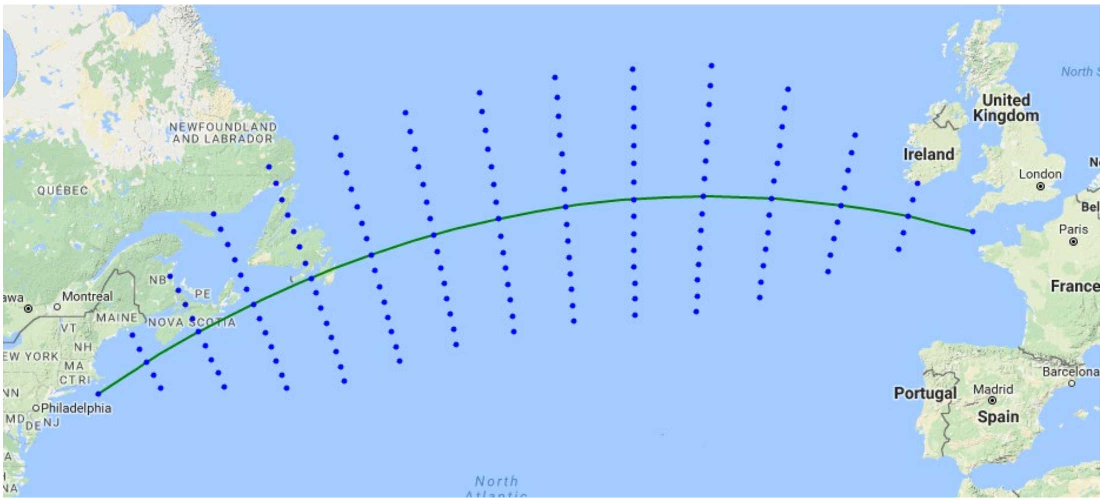
Model	Unit	35,500DWT Bulk Carrier
Ship Type	-	Bulk Carrier
L_{pp}	m	172
B	m	30
T	m	10.1
Main engine type	-	MAN B&W 5S50ME-II9.2
Propeller Diameter	m	5.8 (F.P.P.)

The shipping area is from west end of the English Channel to the estuary of New York. The departure and destination points are given as 5°10'W \ 49°18'N and 70°31'W \ 40°48'N respectively. Departure time is 2014-01-05, 05:00. The grids system has 15 stages with 350 km distance per stage, and every stage has maximum 15 vertical waypoints with equal distance of 50 nautical miles. Here, in consideration of reducing calculation time without skewing results, based on the experience with the system, the waypoint resolution would be better set as 15 stages with maximum 15 vertical waypoints. Ship speed ranges from minimum 4 knots to maximum 20 knots with the interval speed 0.1 knot. The required ETA is set at 227 hours (average 12 knots).

The grids system of this case study can be seen in Figure 6.6. The original grids system is shown in Figure 6.6 (a). The red waypoints in the figure indicate that they are detected on land by land avoidance function. These waypoints will not store any results on land. They demonstrate the effectiveness of the land avoidance function once again. The redefined grids system is shown in Figure 6.6 (b), which is also the grids system adopted in this case study.



(a) Original grids system of case study



(b) Redefined grids system of case study

Figure 6.6 Comparison of grids system before and after upgrade (Map data ©2017 Google)

After performing the calculations, it is found that results obtained before and after the system upgrade including average speed sets, duration and fuel consumption at each stage and shipping route are exactly same, which are listed in Table 6.3, while the calculation time are 16.2 hours and 28 minutes respectively. This means the optimal voyage plan obtained has not been changed at all, but the computational efficiency has improved a lot.

Table 6.3 Optimum route results before and after the system upgrades

Stage	Speed (knots)	Duration (hours)	FC (tonnes)
1	11.8	16.5	9.41
2	11.6	17.6	9.76
3	12.1	16.1	10.13
4	12.1	16.1	9.69
5	12.4	15.7	10.81
6	12.5	15.6	11.08
7	12.1	16.1	9.70
8	12	16.3	9.42
9	12.1	16.1	9.96
10	12.1	16.1	9.96
11	12	16.5	9.66
12	12.1	16.1	9.96
13	12.1	16.1	9.96
14	12.1	16.1	9.65
The whole voyage	Average Speed (knots)	Total Duration (hours)	Total FC (tonnes)
	12.08	227	139.16

After applying all the methods mentioned above to the system, without changing the accuracy of results, the working efficiency of this system almost increases 35 times, which shows these upgrade methods are quite effective. Besides, this also means the optimum route calculation can be finished within half an hour so that these methods make the ship weather routing system have more practical significance. The final minimum fuel consumption routes under this ETA requirement together with great circle and grids system on the map are shown in Figure 6.7.

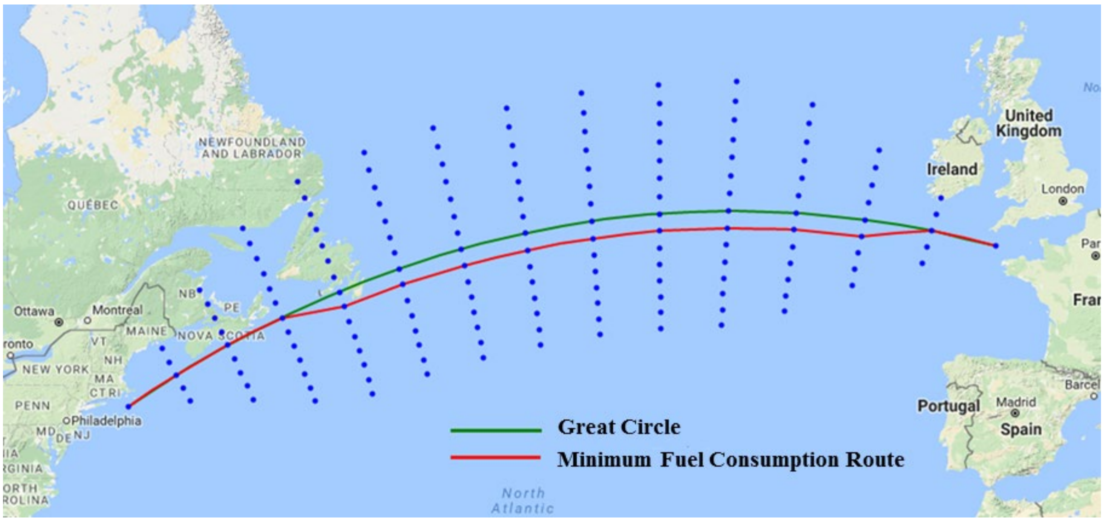


Figure 6.7 Great circle and optimum route of the case study (Map data ©2017 Google)

6.4 Conclusion

The system had low working efficiency when it was first developed. Therefore, seven effective methods are designed to increase the efficiency. They are respectively: Create ship performance database, Redefine ship travel principle and adjust the grids system scale, Merge ship safety module to ship performance prediction module, Delete results in every waypoint which cannot meet the time schedule, Set the speed control parameter, Delete results in every waypoint which cannot meet expected fuel consumption and optimise programming codes. The case study shows the whole ship weather routing system works well, and based on these seven methods, the total working efficiency of this system can increase almost 35 times without affecting the accuracy of the optimum result. These methods may provide some inspiration for further similar system development.

7 Case Studies for the Ship Weather Routing System

7.1 Introduction

Chapters 5 and 6 have introduced the weather routing system in detail. This chapter will carry out two case studies to formally verify the proposed weather routing system. The two case studies will cover two shipping areas, and the second case study will cover four seasons. These representative case studies will demonstrate the effectiveness of the system.

7.2 Case study 1

In this case study, the ship model and shipping area are same to the case study in Section 6.3. A 35,500 DWT Bulk Carrier sails from 5°10'W \ 49°18'N to 70°31'W \ 40°48'N. The grids system has 15 stages, and every stage has maximum 15 vertical waypoints with equal distance of 50 nautical miles. The grids system of this case study is attached again in Figure 7.1. Ship speed ranges from minimum 4 knots to 20 knots with the interval speed 0.1 knot. Departure time is 2014-01-05, 06:00. The ETA is set at 227 hours (average 12 knots), and interest ETA range is 6 hours (within plus or minus 3 hours). The accuracy of the ETA only retains one decimal place.

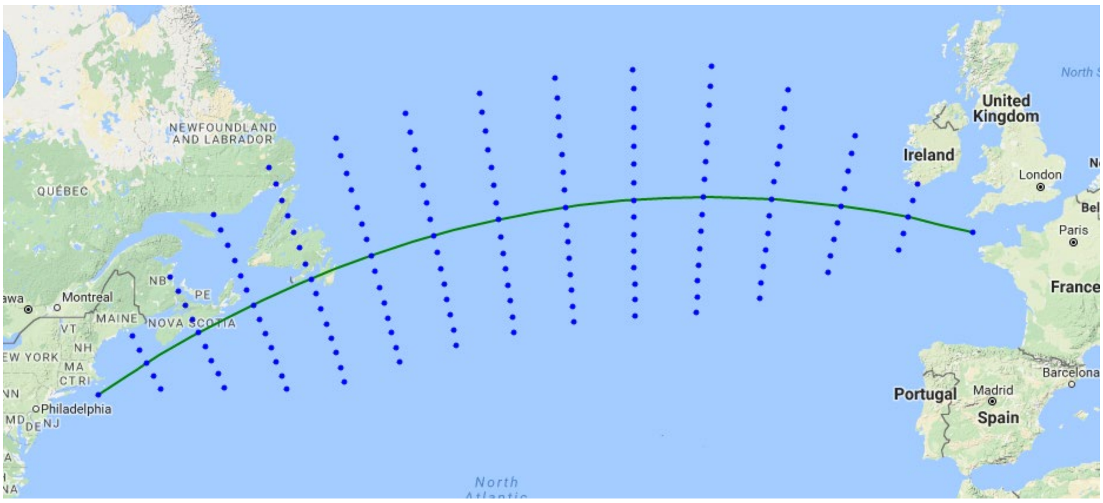
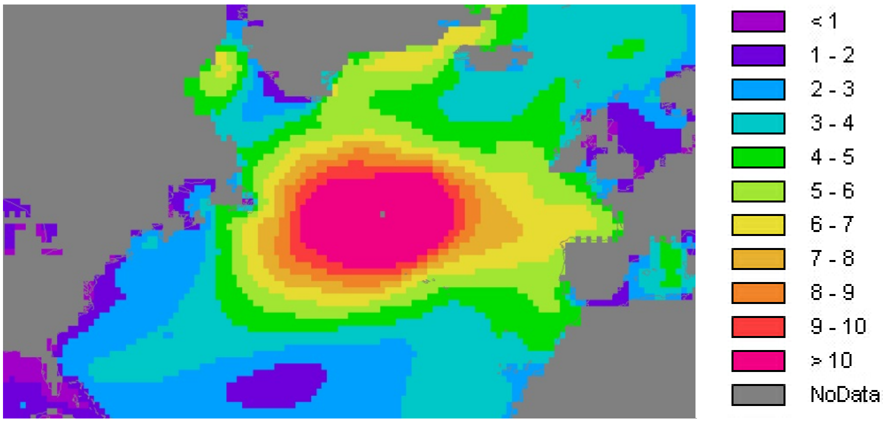
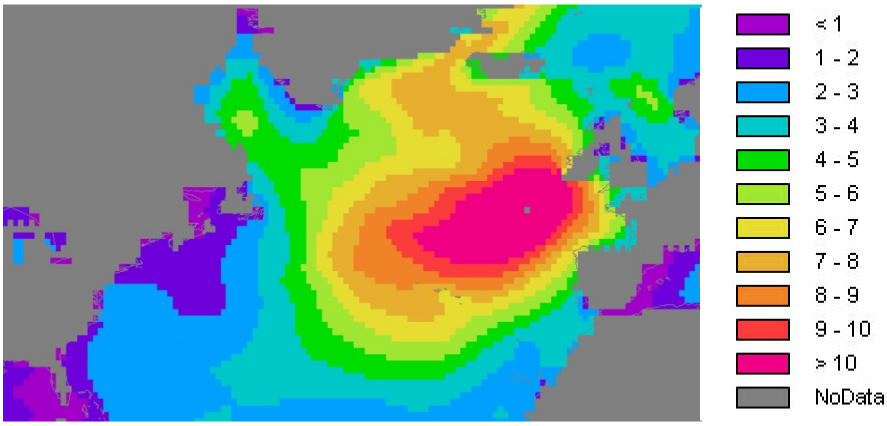


Figure 7.1 Grids system of case study 1 (Map data ©2016 Google)

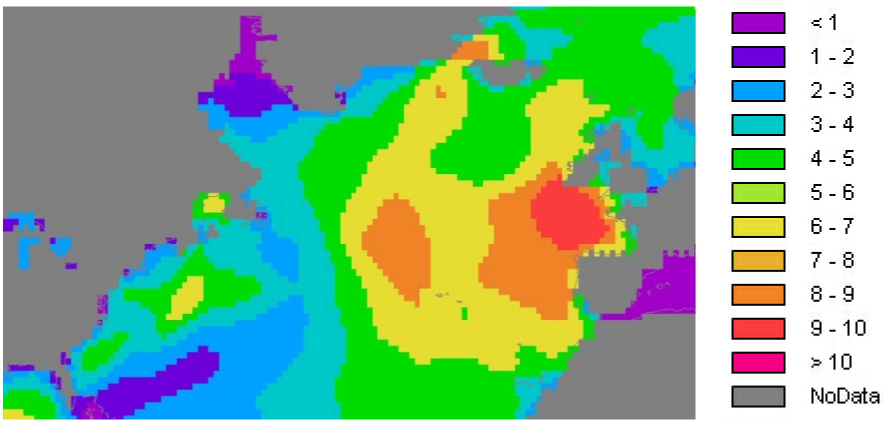
The sequence of Figure 7.2 (a), Figure 7.2 (b) and Figure 7.2 (c) illustrates the three days' significant wave height changing from departure time in the shipping area.



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



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



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

Figure 7.2 Significant wave height changes in three days

As can be seen in Figure 7.2, within first two days after the ship's departure, there will be a severe weather conditions (pink colour) gradually moving eastward and eventually dissipating. This weather condition will affect the final result. This also proves the weather routing system can read the weather data well.

The weather routing optimisation Pareto front results are shown in Figure 7.3.

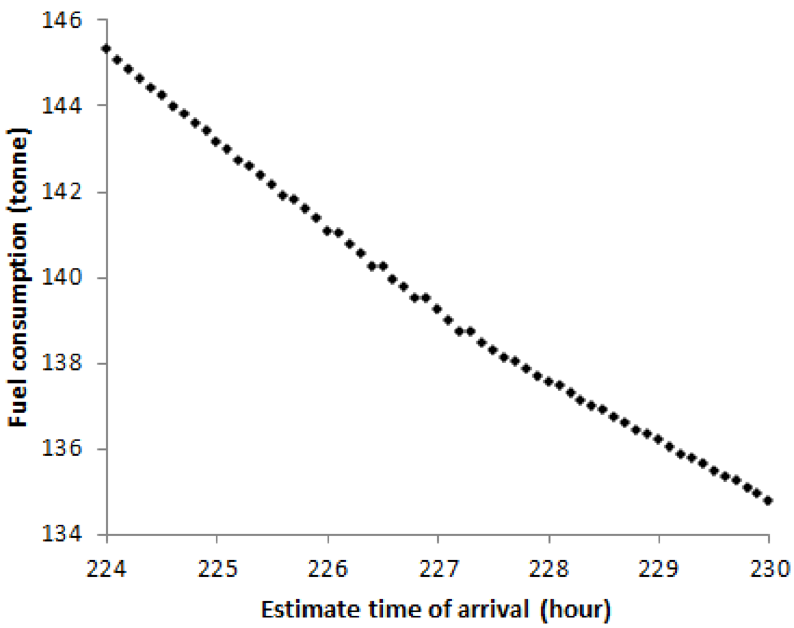


Figure 7.3 Pareto front of case study

It can be seen from Figure 7.3, 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. Average 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 7.4, Figure 7.5 and Figure 7.6.

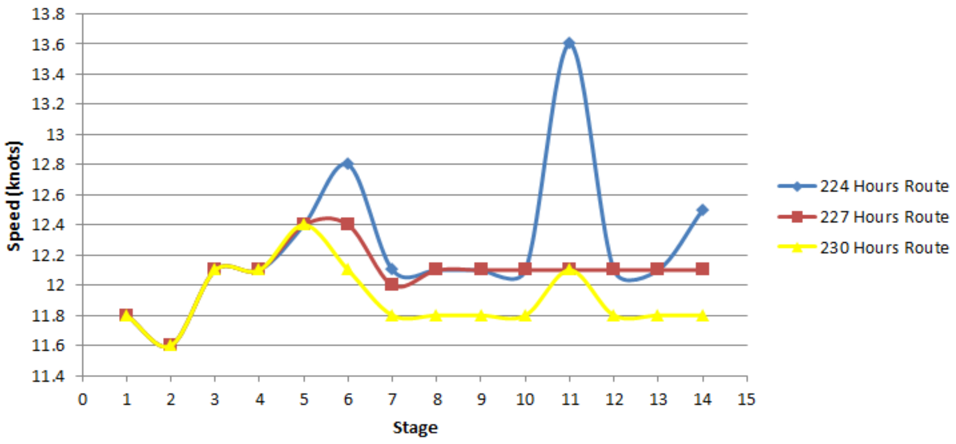


Figure 7.4 Average ship speed at each stage

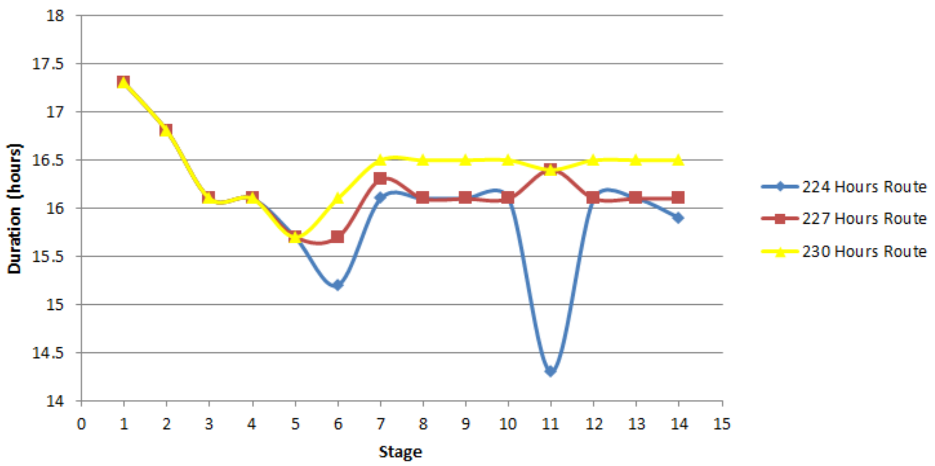


Figure 7.5 Duration at each stage

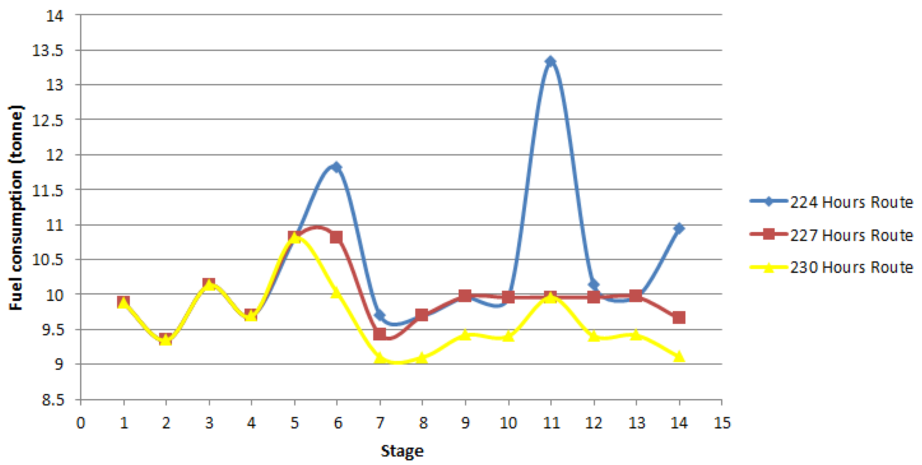


Figure 7.6 Fuel consumption at each stage

As can be seen from Figure 7.4, Figure 7.5 and Figure 7.6, in first 6 stages, all the trends of speed, duration and fuel consumption in the bulk carrier shipping are exactly same. From stage 6, 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.

A rule can be extracted from the results that, taking the 224 hours result as a reference, if the ETA is properly extended by three hours to 227 hours, the fuel consumption will be reduced from 145.34 tonnes to 139.24 tonnes, which means that 4.20% of the fuel consumption can be saved, and if ETA is further extended by six hours to 230 hours, the fuel consumption could decrease by 7.27% to 134.78 tonnes. It can be seen that the appropriate increase of ETA have a big impact on reducing fuel consumption, and the profit generated due to the reduced fuel consumption should not be underestimated. The practical significance of this conclusion is that the operator can plan the sailing time in advance based on the predicted results before the ship leaves the port, and reduce the fuel consumption as much as possible to increase profits without violating the chartering contract. Or the operator can also negotiate and sign a contract with the cargo owner according to the predicted relationship between ETA and fuel consumption. In this case study, the ETA range is limited to only six hours, which can be further extended to a larger range required by the operator.

Take the 224-hour route as an example, its wave height information at each stage can be also extracted for analysis. A Comparison of the wave height and the ship speed at each stage is shown in Figure 7.7. A general trend can be seen that when a ship encounters a sea state of high wave height during navigation, it will reduce the speed to cope with the severe waves, and when the ship encounters mild waves, it will perform a speedier operation. From Figure 7.7, it also can be seen that when the ship is traveling to the second and third stages, it will encounter more severe weather conditions, which coincides with the bad weather area found in Figure 7.2. The ship will travel at a lower speed in this weather condition. When the bad weather passed, the ship will gradually accelerate. This also proves that the weather routing system can effectively predict the ship's response to different wave conditions.

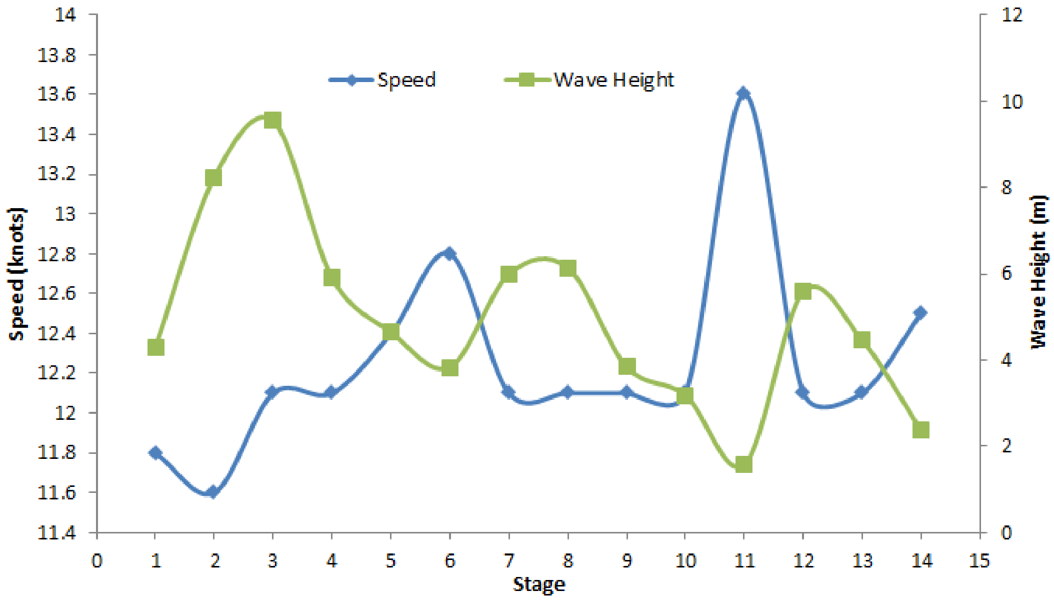


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Figure 7.7 Speed vs wave height for 224 hours route

The results show that the voyage optimisation model works very well towards energy efficient ship operations. These three typical routes together with a great circle are shown in Figure 7.8.

Figure 7.8 Optimal routes based on different requirements (Map data ©2016 Google)

7.3 Case study 2

In this case study, the ship model is still this 35,500DWT bulk carrier. The shipping area is from Dubai to the middle of the India Ocean, but the ship should travel along the west end of India. The departure and destination points are respectively 56°51'E\ 25°15'N and 92°22'E \8°13'S. The grids system has 20 stages, and every stage has maximum 15 vertical waypoints with equal distance of 30 nautical miles. Ship speed ranges from minimum 9 knots to maximum 16 knots with the interval speed 0.1 knot. The required ETA is set at 242 hours.

7.3.1 Case study 2.1

In order to see the benefits of the model, the speed sets under six different conditions are selected for comparison, which are shown as below:

Speed Set A - Actual route and actual voyage speed as recorded in ship noon report ;

Speed Set B - Actual route and optimum speed with identical ETA;

Speed Set C - Global Optimisation with identical ETA;

Speed Set D - Global Optimisation with 3% less ETA;

Speed Set E - Global Optimisation with 3% more ETA;

Speed Set F - Global Optimisation with 5% more ETA.

Global optimisation means optimise both speed and direction at the same time. So the result route may be different from the actual route recorded in ship noon report. All of above have same departure time at 2015-05-13, 23:00. The results are shown in Table 7.1.

Table 7.1 Ship operational performance of different speed sets for case study 2.1

Stage	Speed Set A (knots)	Speed Set B (knots)	Speed Set C (knots)	Speed Set D (knots)	Speed Set E (knots)	Speed Set F (knots)
1	12.5	12.8	13.0	13.0	13.2	12.8
2	12.5	13.2	13.2	13.2	12.6	13.2
3	12.7	12.6	13.0	13.0	12.6	12.6
4	12.5	12.6	13.0	12.6	9.7	12.6
5	12.4	10.7	10.1	11.9	12.6	9.7
6	13.0	12.8	12.6	12.8	11.9	12.6
7	12.8	12.1	12.1	12.1	12.1	11.9
8	12.6	12.6	12.6	13.0	12.6	11.9
9	12.4	13.6	12.6	13.0	12.1	12.6
10	12.1	13.0	12.1	13.0	11.9	11.9
11	13.2	12.6	13.4	13.4	12.6	11.9
12	12.5	13.0	12.6	13.2	12.1	12.6
13	12.4	9.7	12.1	12.6	9.7	9.7
14	12.3	12.1	11.3	12.1	11.9	9.7
15	13.1	12.1	12.1	12.2	12.6	11.9
16	12.9	12.6	12.6	12.6	13.2	12.6
17	12.4	12.8	13.2	13.2	13.4	13.2
18	11.9	13.2	13.0	13.2	13.2	13.2
19	11.8	12.8	13.2	13.4	13.2	13.2
Voyage Duration(hours)	242	242	242	235	249	254
FC (tonnes)	135.23	133.24	133.06	141.23	125.69	121.37
FC compared to Speed Set A	0	-1.47%	-1.60%	4.43%	-7.05%	-10.2%

As can be seen from Table 7.1, compared to Speed Set A, the speed optimisation (Speed Set B) for a fixed route will provide 1.47% fuel savings, while global optimisation (Speed Set C, both speed and direction optimisation) can provide 1.60% fuel savings. This means that on this fixed route, only speed optimisation can save 1.47% fuel compared to the original navigation plan. When the speed and direction are both optimised at the same time, it can save 1.60% fuels. It can be seen that the global optimisation will bring more fuel saving benefits than the simple speed optimisation.

Taking Speed Set C which has ETA of 242 as a reference, for Speed Set D, if ETA is reduced by 7 hours to 235 hours, the ship will consume 6 tonnes more fuels, which means that when ETA is reduced by 3%, the ship will consume 4.43% more fuels; For Speed Set E, when the ETA is extended by 7 hours to 249 hours, the ship will save 9.69 tons of fuel consumption, that is, 3% longer ETA will generate 7.05% fuel savings; Similarly, for Speed Set F, if ETA is further extended by 5% to 254 hours, fuel consumption will be reduced by 10.2% to 121.37 tons. Shipping companies can plan shipping time based on this rule to increase profits.

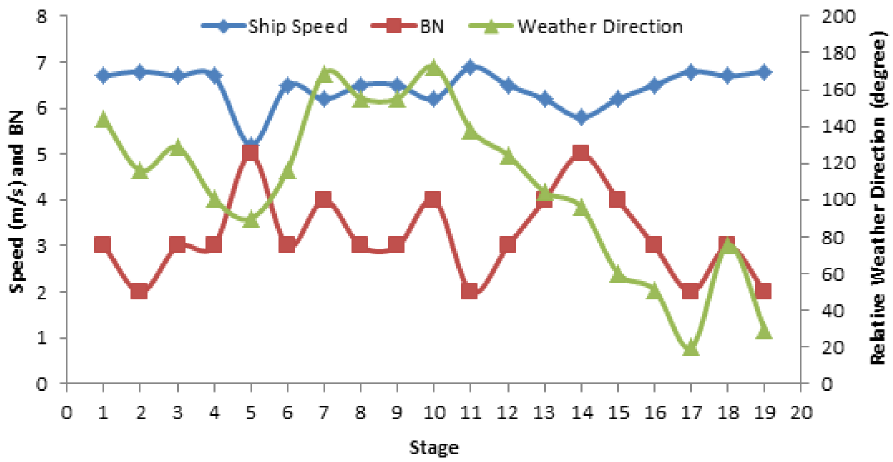


Figure 7.9 The speed and weather condition distribution of Speed Set C

The speed, BN (Beaufort number, which reflects wind force and significant wave height) and relative weather direction in each stage of Speed Set C are extracted in Figure 7.9. To compare more clearly, the speed unit has been changed from knots to m/s. It can be seen that the ship speed has a very good response to different weather conditions. When BN is increasing, the ship will reduce speed and will speed up again when the BN is low. The impact factor of BN is also higher than relative weather directions. At stage 16 to 19, although the ship travels in head sea or beam sea (relative weather direction from 0° to 60°), because the BN is relatively low, the ship can still travel at relatively higher speed. All of these routes are drawn on the map in Figure 7.10.

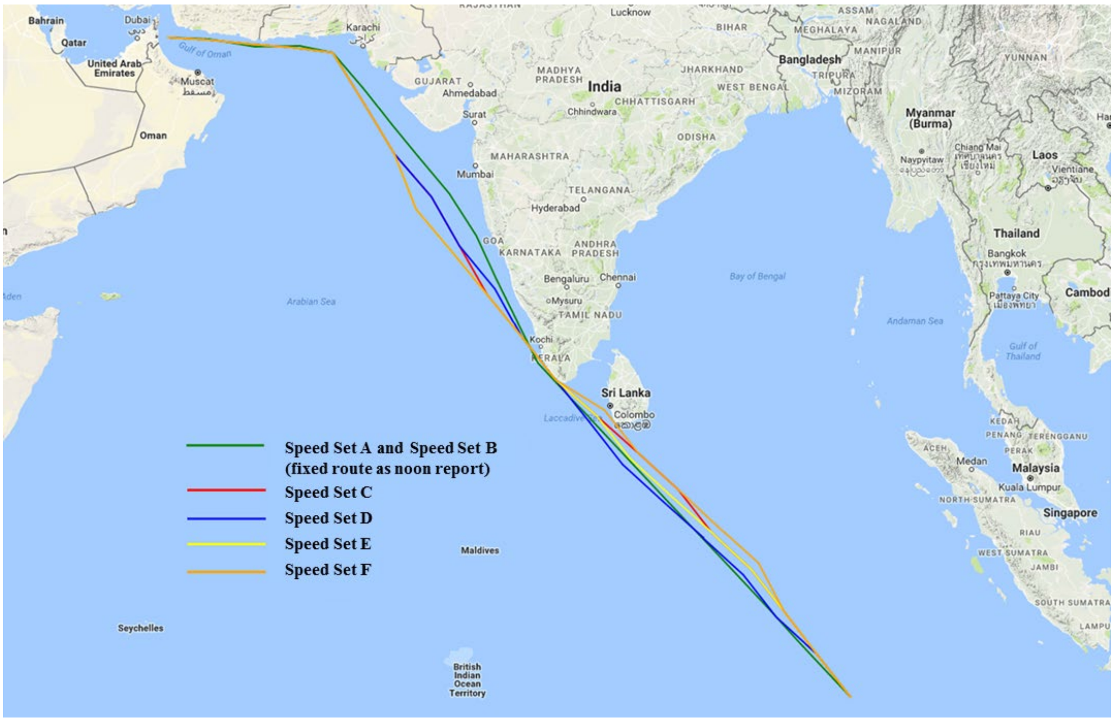


Figure 7.10 Optimal routes based on different conditions for case study 2.1 (Map data ©2017 Google)

7.3.2 Case study 2.2

In order to see the weather routing benefits under various weather condition more clearly, another three case studies with departures at different seasons are carried out. Together with the Speed Set C, all the shipping plans are listed as below and all of these simulations have same ETA of 242 hours. The results are shown in Table 7.2.

Speed Set G - Global Optimisation with the departure time of 2015-02-13, 23:00;

Speed Set C - Global Optimisation with the departure time of 2015-05-13, 23:00;

Speed Set H - Global Optimisation with the departure time of 2015-08-13, 23:00;

Speed Set I - Global Optimisation with the departure time of 2015-11-13, 23:00.

Table 7.2 Ship operational performance of different speed sets for case study 2.2

Stage	Speed Set G FEB (knots)	Speed Set C MAY (knots)	Speed Set H AUG (knots)	Speed Set I NOV (knots)
1	13.2	13.0	13.2	12.6
2	13.0	13.2	13.2	11.9
3	11.9	13.0	12.6	11.9
4	11.9	13.0	13.2	11.9
5	11.9	10.1	12.1	13.2
6	11.9	12.6	12.1	11.9
7	11.9	12.1	12.6	11.9
8	12.6	12.6	12.4	11.9
9	11.9	12.6	12.6	11.9
10	13.2	12.1	12.6	11.9
11	13.2	13.4	12.6	13.2
12	13.2	12.6	12.6	13.2
13	12.6	12.1	12.1	13.4
14	9.7	11.3	12.1	12.6
15	12.6	12.1	13.2	13.2
16	13.2	12.6	12.6	12.6
17	13.4	13.2	12.2	12.6
18	13.2	13.0	10.9	12.6
19	13.2	13.2	12.2	12.6
Average BN	3	3.21	3.32	3.05
Voyage Duration(hours)	242	242	242	242
FC (tonnes)	132.33	133.06	136.13	135.40
FC compared to Speed Set C	-0.54%	0	2.31%	1.76%

As it can be seen from Table 7.2, if the ship departures at different seasons, the corresponding fuel consumption will change slightly. Compared with Speed Set C (May), the fuel savings are respectively 0.54% less for Speed Set G (February), 2.31% more for Speed Set H (August) and 1.76% more for speed Set I (November). In the same navigation route, the vessel consumed the least of fuel in February and consumed the most fuel in August. This also provides a reference for shipping companies to plan the sailing season.

The average BN the ship meets at all the four routes are also listed in Table 7.2 and more detailed ship average speed, BN and relative weather direction in each stage of all the Speed Set are extracted in Figure 7.11, Figure 7.12 and Figure 7.13. It can be seen from these figures that the ship operations have a very good response to different weather conditions. When the ship encounters sea states with strong wind, it will decrease the sailing speed appropriately. Even if the wind is downwind which is good for sailing, if the wind goes strong, the ship should decelerate properly to ensure safety; When the ship encounters mild sea conditions, the ship will sail at a relatively high speed. Even if there is a headwind condition, due to the weaker wind only has limited impact on the ship, the ship will remain sailing at a relatively high speed.

As a result of the previous three routes, a general rule is that the stronger the wind the ship encounters, the more fuel it will consume. However, the Speed set I has a different trend, which has relatively lower average BN but has more fuel consumption comparing to Speed Set C. But after taking relative weather direction into consideration, it can be found that Speed Set I has met relatively more head sea and bow sea situations, which will definitely increase fuel consumption. Therefore, the results are reasonable. It can also be seen that the system is very sensitive to the impact of the weather and can basically reflect the impact of the weather on the ship navigation, which also proves the presented weather routing system works very well.

At last, all of these routes are drawn on the map in Figure 7.14.

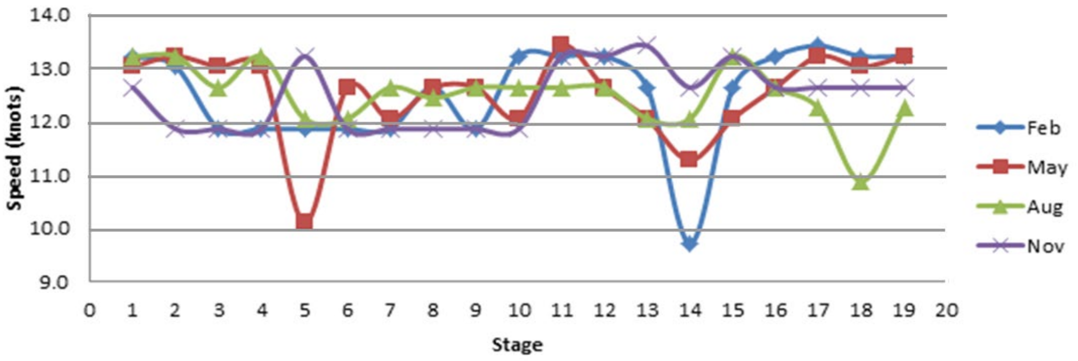


Figure 7.11 Speed distribution based on different conditions for case study 2.2

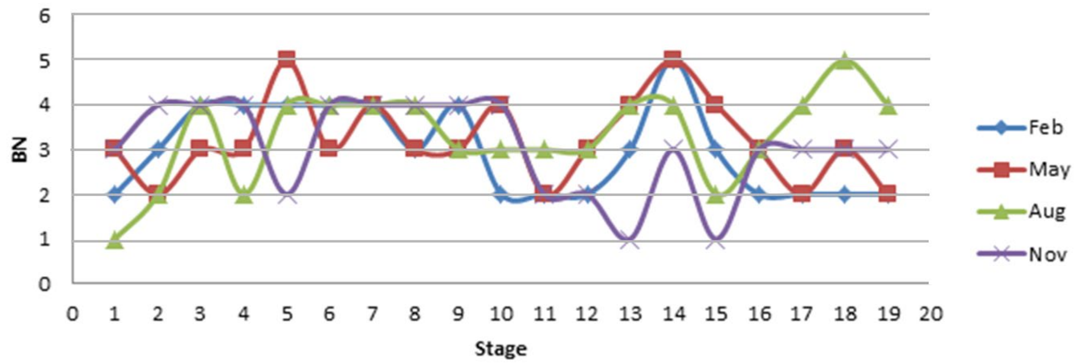


Figure 7.12 BN distribution based on different conditions for case study 2.2

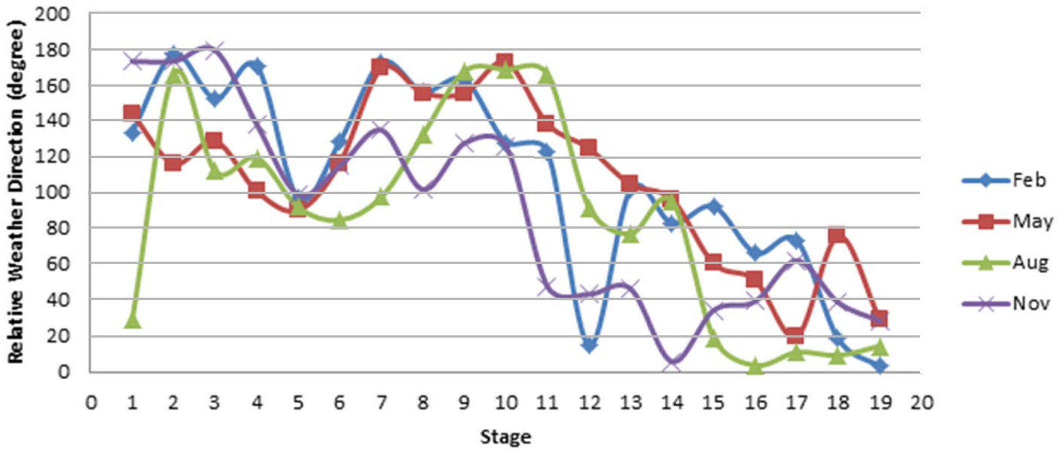


Figure 7.13 Relative weather direction distribution based on different conditions for case study 2.2

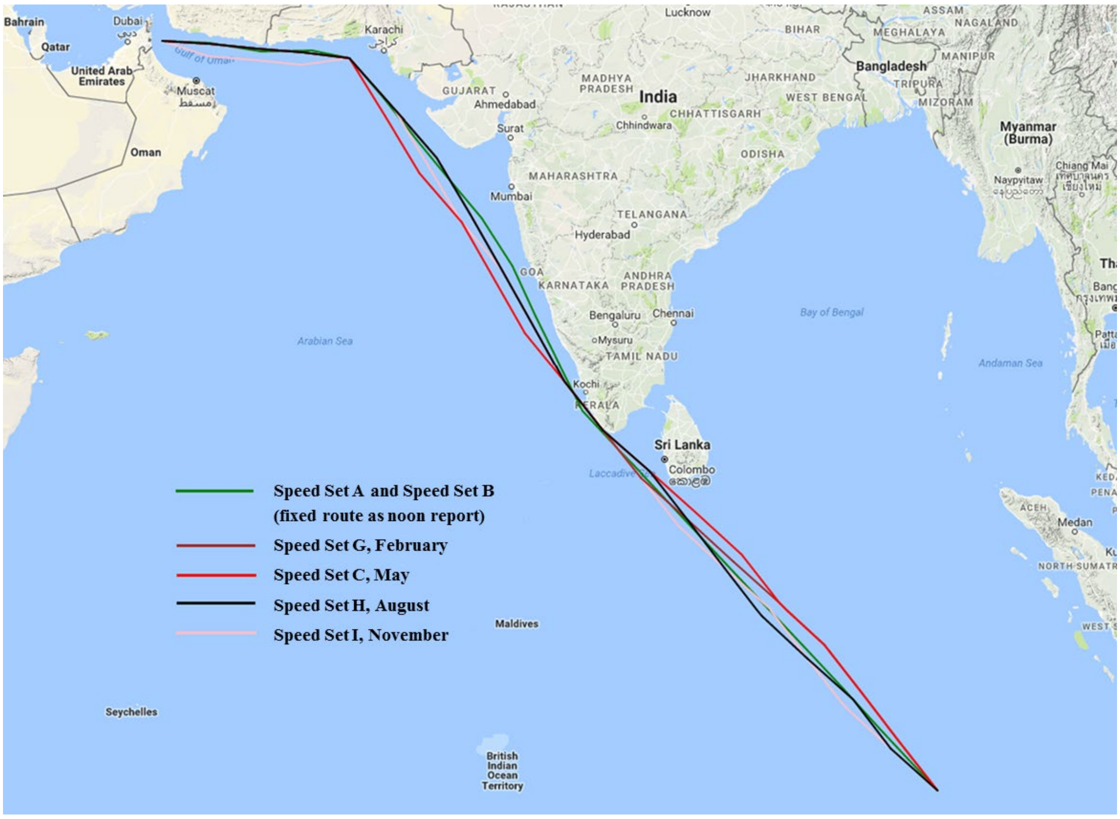


Figure 7.14 Optimal routes based on different conditions for case study 2.2 (Map data ©2017 Google)

7.4 Conclusion

Several case studies with a 35,500 DWT bulk carrier have been made in this chapter. These case studies are representative conditions, which cover two sea areas and multiple seasons. As can be seen from results, this system can reflect the impact of the weather on the ship navigation and certainly obtain more reliable ship operational results. Several conclusions can be drawn that the proposed system can help the case study ship save almost 1.5% fuel consumptions through the voyage optimisation; Different sailing seasons may lead to different fuel consumption results; A proper extension of ETA would save more fuel, which would make it possible to reduce fuel consumption and increase profits by modifying shipping schedules.

These case studies prove that, the weather routing system proposed in this study can be used to complete various types of shipping simulations. It can provide stakeholders with the required results as a reference to help them have more informed contract negotiations and reduce fuel consumption and increase profits.

8 Assessing the True Performance of Ships Fitted with Wind Assist Technologies: Flettner Rotor Case Study

8.1 Introduction

To tackle global warming, the maritime sector is trying alternative power sources to reduce the carbon emissions from ships. Wind assist technologies are considered to make full use of renewable alternative power sources and ships designed with such technologies may provide the important step toward decarbonisation. Among many effective measures, Flettner rotor, as one of the wind assist technologies, is increasingly becoming a topic of interest within the shipping industry. The study in this chapter aims to make an in-depth discussion on the benefits from Flettner rotor in terms of energy efficiency and serious renewable alternative power source for ships.

There are three reasons why Flettner rotor technology was chosen as the research object in this chapter.

1. As a green energy source, wind energy has the characteristics of clean, environmentally friendly, renewable and low cost. Research on wind assist technologies, especially Flettner rotor technology has become a hot topic.

2. Flettner rotor technology is very sensitive to wind and can better reflects the impact of wind on shipping. The performance of a ship fitted with Flettner rotor is very much dependent on the wind magnitude and direction, which are random by nature.

3. The research on Flettner rotor technology is ideal to show the benefits of the proposed weather routing system.

In this chapter, many case studies are carried out based on a generic ship with and without rotors. Different combinations of several traditional routes including both outward and return directions, different departure time throughout the whole operation year and average slow, medium and fast ship speeds are taken into account as shipping conditions for comparison. Finally, the benefit obtained through Flettner rotor technology - in various shipping routes, departure times and ship speeds - is presented and a framework for assessing the performance of wind assist technology is proposed.

8.2 Working principles of the Flettner rotor

As mentioned in Section 2.5.1, a Flettner rotor is a smooth cylinder with disc end plates which is spun along its long axis and, as air passes at right angles across it, the Magnus effect causes an aerodynamic force to be generated in the third dimension.

So what is Magnus effect? When the rotational angular velocity vector of a rotational object does not coincide with the flight velocity vector of the object, a lateral force will be generated in a direction perpendicular to the plane formed by the rotational angular velocity vector and the panning velocity vector. The phenomenon that the trajectory of an object is deflected by this lateral force is called the Magnus effect. The reason why the rotating object can generate force in the lateral direction is that the rotation of the object can drive the surrounding fluid to rotate, so that the fluid velocity on one side of the object increases and the fluid velocity on the other side decreases.

According to Bernoulli's theorem, the increase of fluid velocity will cause the pressure to decrease, and the decrease of the fluid velocity will result in the increase of pressure, which will result in a lateral pressure differential on the rotating object and create a lateral force. At the same time, because the lateral force is perpendicular to the moving direction of the object, this force mainly changes the direction of the flying speed, which is the centripetal force in the movement of the object, and thus leads to the change of the flying direction of the object. Explaining by the theory of potential flow, the flying motion of a rotating object can be simplified to the "straight uniform flow + point vortex + dipole" motion, in which the point vortex is the source of lift. The Magnus effect is explained clearly in Figure 8.1.

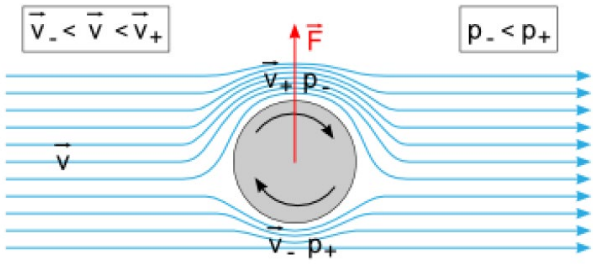


Figure 8.1 The Magnus effect on a rotating cylinder (Enercon, 2013)

The specific application of the Magnus effect to a ship is to install a Flettner rotor for the ship, which usually consists of a cylinder with an end plate fixed to the top, mounted vertically on the deck of the ship (Pearson, 2014). When the ship encounters a crosswind, the cylinder rotates to create a force perpendicular to the wind direction that propels the ship forward. However, it is difficult for the wind direction to be completely perpendicular to the forward direction of the ship, so propellers are required to provide a corresponding force to form a resultant force in the forward direction to push the ship forward, as shown in Figure 8.2. Several large cylinders on the ship are equipped with drive equipment that can make the rotors rotate at different speeds. The propulsion control system is complex and it can control the propeller to match the wind at any time.

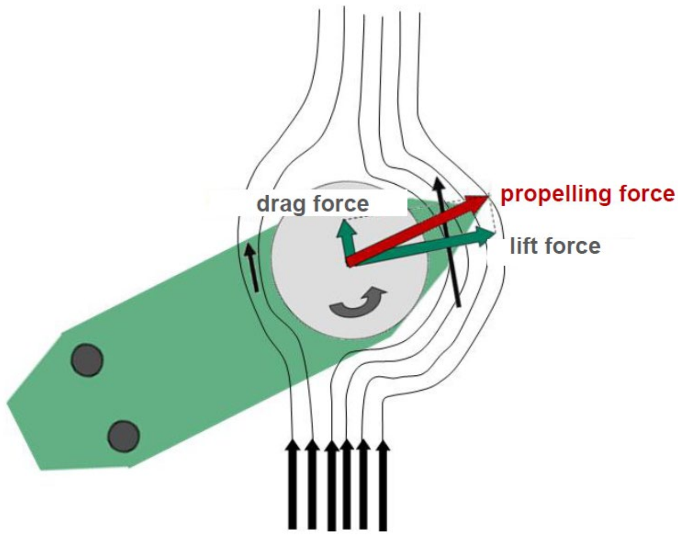


Figure 8.2 The basic principle of the Flettner rotor (Enercon, 2013)

The relationship among the wind direction, the ship course and the generated thrust is shown in Figure 8.3. True wind represents the wind speed and direction of the natural world, and the advancing ship will produce the opposite wind direction. The combination of the two wind vectors produces an apparent wind. The apparent wind is the wind experienced by an observer in motion and is the relative velocity of the wind in relation to the observer. What the crew measured on the ship and used as a navigational reference was the apparent wind. It can be seen from this vector triangle that the apparent wind is minimum when the true wind is downwind, that is, the ship velocity direction is same to the true wind direction. When the true wind is upwind, that is, the true wind direction is opposite to the ship forward direction, the apparent wind is maximum. However, the upwind will impede the shipping progress. The generated wind energy is insufficient to offset the increased resistance. Therefore, the most favourable wind is the largest apparent wind under the condition of minimum upwind. That is the wind perpendicular to the ship advancing direction which is so called crosswind. It can be also seen from Figure 8.3, the crosswind perpendicular to ship velocity direction will finally generate a strong lift by the rotor rotation and this lift is consistent with ship advancing direction and is certainly favourable for ship propulsion.

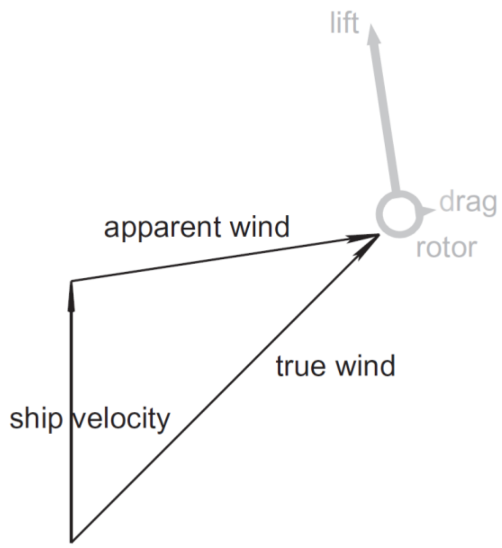


Figure 8.3 Schematic of wind and ship velocity, and the resulting lift and drag force (Traut et al, 2014)

The theoretical relationship between the wind direction and energy saving when the ship travels with the velocity of 16 knots and in the wind of 6 BFT can be seen in Figure 8.4. The ship saved the most energy (almost 46%) in crosswind (90º or 270º). In fact, the research of current wind assisted propulsion mainly focuses on how to take advantage of crosswind as much as possible.

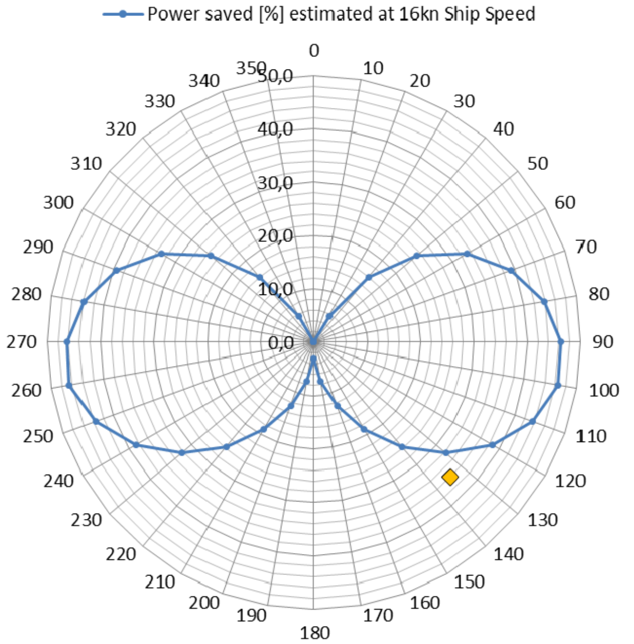


Figure 8.4 Saved power (%) vs Wind at 6 BFT (Enercon, 2013)

There are three important parameters for the design and performance calculation of the Flettner rotor, which are respectively aspect ratio, end plate and velocity ratio.

Aspect ratio is the ratio between the height and diameter of the cylinder. It affects the Flettner rotor effectiveness in producing aerodynamic forces significantly. When a Flettner rotor is designed with a higher aspect ratio, it will perform much like a wing, with tip vortices that take part in the lift production (De Marco, et al, 2016). Swanson (1961) also argued that the smaller the aspect ratio the smaller the maximum lift obtained and the smaller the velocity ratio at which this maximum is reached.

End Plate, also called Thom disk, is a round plate installed on the top of the rotor cylinder. It can affect the 3D flow at the tip of the Flettner rotor and can increase the lift coefficient. It can even produce almost double the lift at high velocity ratios (De Marco, et al, 2016). But in general cases, the end plate can not always enhance the propulsion efficiency of the whole ship, because rotating such a structure also requires more energy.

Velocity ratio, also called spin ratio, is the key parameter to determine the generated lift and drag from a rotating cylinder. The calculation of velocity ratio can be explained as:

$$\alpha = \frac{V}{U} \tag{8.1}$$

Where, α is velocity ratio, U is the apparent wind speed and V is the circumferential velocity which can be calculated by:

$$V = \frac{d}{2}\Omega \cdot \frac{\pi}{180} \tag{8.2}$$

Where, d is the diameter of the cylinder and Ω is the angular velocity (degree/s).

According to Knif (2009) and Suominen (2015), from the existing experimental data, the lift coefficient C_L and drag coefficient C_D can be expressed as a function of velocity ratio α :

$$C_L(\alpha) = -0.8 + \frac{12}{1+e^{-\frac{\alpha-2}{0.8}}} \tag{8.3}$$

$$C_D(\alpha) = 0.6 + \frac{3.8}{3+e^{-(\alpha-5)}} \tag{8.4}$$

As the lift and drag are always expressed with lift and drag coefficients, the lift and drag generated from the rotating Flettner rotor can be expressed as:

$$L = \frac{1}{2}\rho_{air} C_L S U_0^2 \tag{8.5}$$

$$D = \frac{1}{2}\rho_{air} C_D S U_0^2 \tag{8.6}$$

Where, L is the lift, D is the drag, ρ_{air} is the air density, S is the cylinder projected area and U_0 is the apparent wind speed.

There are also other important factors generated by rotating rotors which affect the ship motions and can not be ignored, like increased heeling moment from side forces and extra rudder drag from increased yaw etc (Pearson, 2014). For example, with the rotors rotating, sometimes the generated side force may become very large when apparent wind angle become extreme. Combined with the vertical high Flettner Rotors, this large side force will create a large heeling moment on the ship and will thus increase the angle of static heel of the ship. Besides, the large sway forces will lead to yaw moments on the ship, which must be balanced by increasing rudder angle. This operation will increase drag and reduce the benefit from the Flettner Rotors.

In order to consider the performance of Flettner rotors fitted ship more comprehensively, a WASPP (Wind Assisted Ship Performance Prediction) model has been developed in 2015 by Strathclyde University SCC project research group (Howett, 2015, 2016).

According to Howett (2015, 2016), WASSP calculates the aerodynamic and hydrodynamic forces and moments from hull, rudder, prop and sails and incorporates added resistance due to waves, leeway and heel based on basic principle of Newtons second law. WASSP is essentially a 4 degrees of freedom balance solution model. It solves to find the equilibrium condition where surge, sway, roll and yaw are balanced when a combination of input parameters are given. Input variables include TWS (True Wind Speed), TWA (True Wind Angle), and can also include ship speed and engine RPM according to different desired output. When added resistance due to waves is considered in the ship performance calculation, wave height and wave angle should be also added in input variables. The calculation process will be repeated for every combination of wind speed, wind angle and ship speed etc. in WASPP, and finally all the results can be exported to a ship performance file for later calculation in the proposed weather routing system.

According to Howett (2016), in WASPP model, bare hull calm water resistance is obtained using Holtrop 1984 method; Added resistance due to waves is obtained using a modified kwon's method; The additional drag due to heel is approximated via a change in wetted surface area; Drag due to leeway is included in the form of hydrodynamic coefficients from the testing of British Bombardier; Drag due to rudder angle is calculated along with standard aerofoil theory assuming a NACA0018 section; Aerodynamic drag of the topsides and superstructure is calculated based on the method described by Blendermann (1994) to find the total resistance of the ship.

Based on above working principles and WASPP model, the operational performance towards energy consumption of a Flettner rotor fitted ship can be accurately calculated.

8.3 Case studies and discussions

A generic motorised KCS container ship fitted with and without 936 m^2 Flettner rotors is taken as the ship model in order to perform the energy saving performance of the ship with Flettner rotor compared to the fully motorised baseline ship. It is worth noting that the KCS container ship is not a ship that was actually built. The reason why it is chosen as a ship model is that the KCS container ship is publicly available data and can be published with experimental routing available. It is an ideal model for the research of wind energy impact.

The main particulars of the ship and propeller are given in Table 8.1.

Table 8.1 Main particulars of KCS container ship

(Simman 2008 website, accessed 2016).

Model	Unit	KCS
Ship Type	-	Container Ship
L_{pp}	m	230
B	m	32.2
T	m	10.8
Propeller Diameter	m	7.9 (F.P.P.)
Flettner Rotor Area	m^2	936

The speed-power curve for pure motorised KCS ship in calm water is shown in Figure 8.5. The main aim of carrying out a systematic calculation is to calculate the real performance of the wind assisted ship and determine the correct way of assessing the performance of the ship fitted with Flettner rotor in real operational conditions by using the actual global routes and corresponding weather conditions. This is very important as the energy saving performance of a ship fitted with fletner rotor very much depends on the availability of the wind in terms of magnitude and direction in the route as they are function of time.

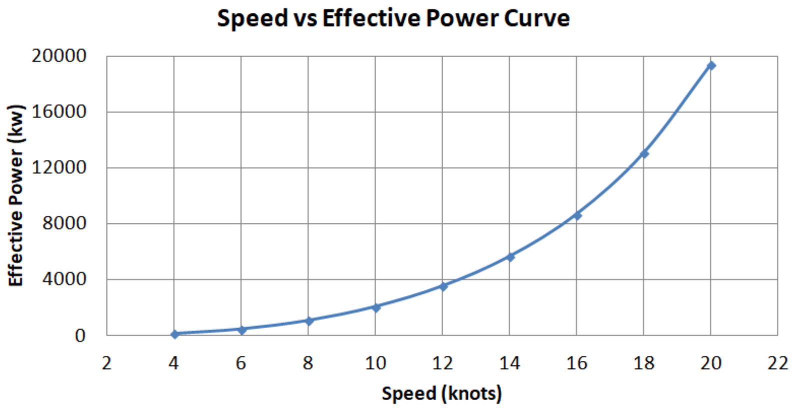


Figure 8.5 Speed - Effective power curve for pure motorised KCS ship in calm water

8.3.1 Case study 1 - various basic case studies

Following parameters are investigated in details:

Effect of average ship speeds: 6knots, 10 knots and 14 knots, represent slower, medium and faster speed respectively.

Effects of shipping season: departure time is at 05:00 am of JAN-05-2014 (Winter), APR-05-2014 (Spring), JUL-05-2014 (Summer), OCT-05-2014 (Autumn).

Effects of the geographical location of routes and the travel direction: Five traditional routes over the world including both outward and return directions are investigated. They cover various common oceans and all the travel directions (North-South and West-East). They are:

- Route 1: from Chiba in Japan to Los Angeles in the USA;
- Route 2: from Rio de Janeiro in Brazil to Cape Town in South Africa;
- Route 3: from Puerto la Cruz in Venezuela to Gibraltar;
- Route 4: from Brisbane in Australia to Yokosuka in Japan;
- Route 5: from Banda Aceh at Malacca to Durban in South Africa.

All of these routes are labelled with the letter "a" and "b", which means the outward direction and return direction respectively.

The shipping area and grids system of these five routes are respectively shown in Figure 8.6, Figure 8.7, Figure 8.8, Figure 8.9 and Figure 8.10.

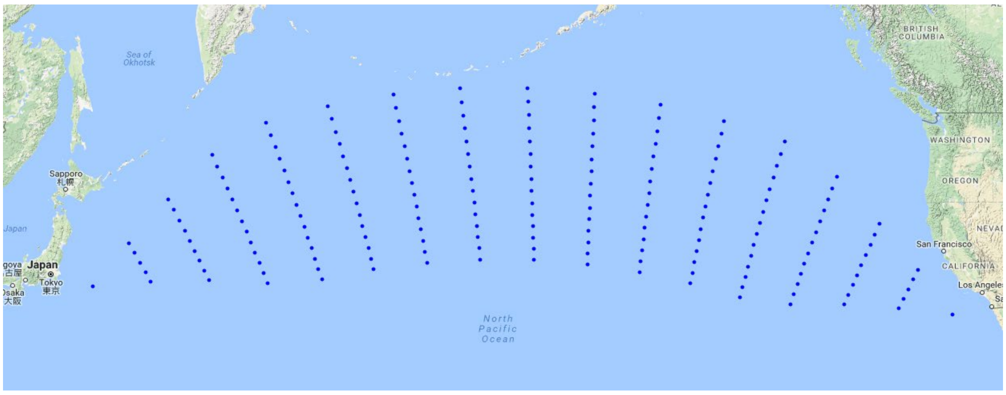


Figure 8.6 Grids system of Route 1 (Chiba in Japan - Los Angeles in the USA) (Map data ©2018 Google)

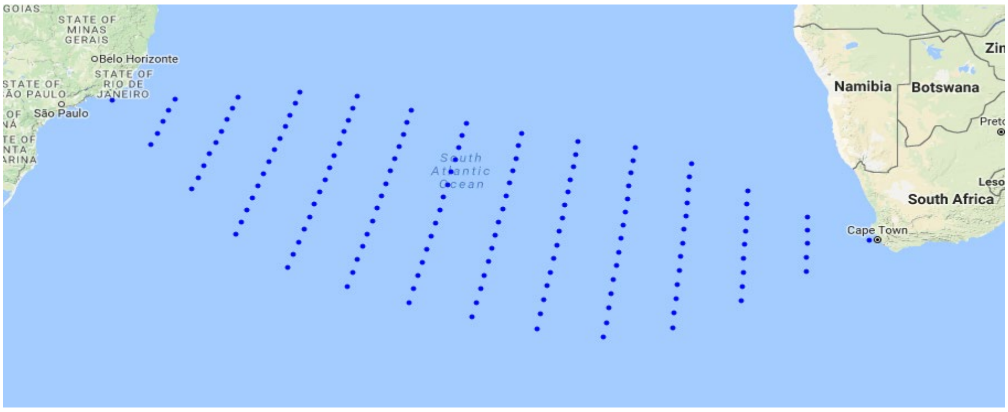


Figure 8.7 Grids system of Route 2 (Rio de Janeiro in Brazil - Cape Town in South Africa) (Map data ©2018 Google)

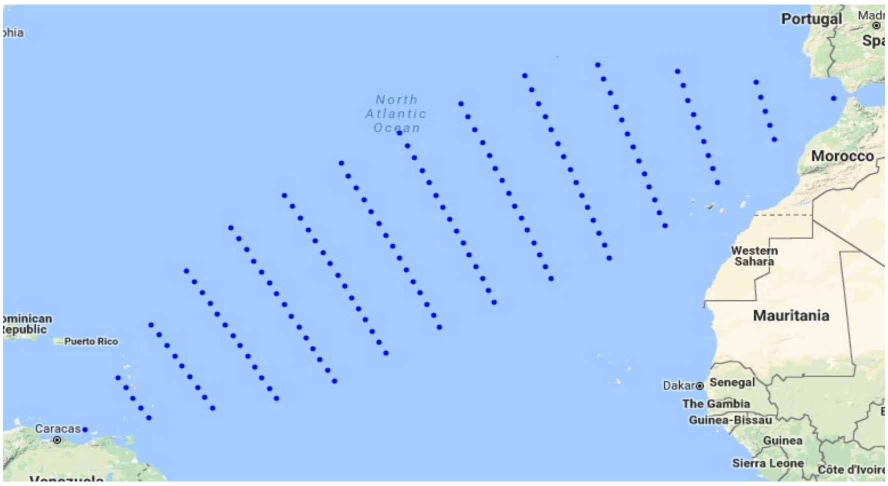


Figure 8.8 Grids system of Route 3 (Puerto la Cruz in Venezuela - Gibraltar) (Map data ©2018 Google)

Figure 8.9 Grids system of Route 4 (Brisbane in Australia - Yokosuka in Japan) (Map data ©2018 Google)

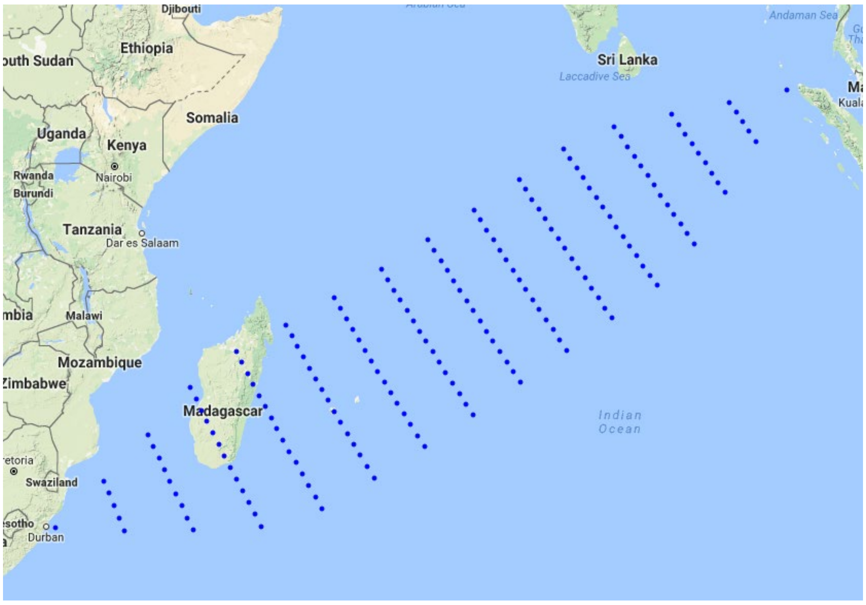


Figure 8.10 Grids system of Route 5 (Banda Aceh at Malacca - Durban in South Africa) (Map data ©2018 Google)

All the results are shown as below, the percentage means how much benefits can be obtained with Flettner rotor technology in terms of fuel consumption saving compared to motorised ship.

Results for Route 1:

Table 8.2 Fuel consumption saving for Route 1

a) Chiba in Japan - Los Angeles in the USA
b) Los Angeles in the USA - Chiba in Japan

Route /Speed	JAN	APR	JUL	OCT	Average	Combined Annual Average
1a / 6 knots	-83.38%	-56.15%	-17.32%	-76.08%	-58.57%	-51.26%
1b / 6 knots	-67.64%	-47.47%	-20.20%	-39.17%	-43.45%	
1a / 10 knots	-33.16%	-28.31%	-1.64%	-25.85%	-22.27%	-16.76%
1b / 10 knots	-15.71%	-12.70%	-5.53%	-11.22%	-11.26%	
1a / 14 knots	-14.18%	-7.61%	0.26%	-12.28%	-8.46%	-5.32%
1b / 14 knots	-2.13%	-0.98%	0.78%	-6.43%	-2.20%	

As can be seen from Table 8.2, for both route 1a and 1b under slower speed and medium speed, the most fuel consumption saving happens in January while the least saving happens in July. It illustrates that for shipping area 1, if the ship speed is not high, winter will be the most favourable season for winds assisted shipping while summer only generates the least benefit in terms of fuel saving. The same situation also happens at route 1a under faster speed, but in July, it shows the ship not only has not fuel saving, but actually needs more fuel for wind assisted shipping, which means the summer season is totally not a good time for the ship travel in area of route 1 under fast speed. For route 1b under faster speed, when the ship sails in summer, it still needs to consume more fuel if fitted with rotors, but the most favourable season for that situation becomes autumn (October) instead of winter (January).

For all three speed conditions, the route 1a will lead to more fuel saving than the return direction route 1b due to the wind direction which affects the performance of Flettner rotor. Besides, as far as annualised savings are concerned, the results show the speed conditions impacting savings from maximum to minimum in proper order are slower speed (-51.26%), medium speed (-16.76%) and faster speed (-5.32%) in shipping area 1. This case study shows these fuel saving percentages are very different, which highly depend on the random wind condition. For the same speed condition, different sailing seasons will have different wind conditions, and different wind conditions will lead to different fuel savings; while different speed conditions will also bring different fuel saving benefits for the same month. Thus, the slower the speed, the more fuel consumption savings will be obtained, and the higher the speed, the less benefit can be obtained from Flettner rotors.

Overall results clearly confirm the general principle with sailing ship performance that Flettner Rotor is beneficial when the ship speed is less than wind speed. Considering the average wind speed available globally, Flettner rotor is more beneficial for the merchant vessels with slower average speed, i.e bulk carrier and tankers.

Results for Route 2:

Table 8.3 Fuel consumption saving for Route 2

a) Rio de Janeiro in Brazil - Cape Town in South Africa
b) Cape Town in South Africa - Rio de Janeiro in Brazil

Route/Speed	JAN	APR	JUL	OCT	Average	Combined Annual Average
2a / 6 knots	-16.93%	-14.71%	-47.76%	-30.99%	-27.71%	-25.5%
2b / 6 knots	-12.87%	-19.96%	-35.08%	-24.3%	-23.22%	
2a / 10 knots	-1.14%	-4.93%	-17.43%	-0.82%	-6.13%	-6.28%
2b / 10 knots	-5.58%	-8.66%	-6.57%	-4.97%	-6.44%	
2a / 14 knots	3.63%	-1.22%	2.58%	4.26%	2.32%	0.28%
2b / 14 knots	-1.66%	-1.87%	-1.05%	-2.41%	-1.75%	

As can be seen from Table 8.3, in area 2, when the ship sails with slower speed, it can achieve relatively large fuel saving (-25.5%) throughout the whole year; when the ship sails with medium speed, it can still achieve good fuel saving (-6.28%); but when the ship speed increases to 14 knots, the situation reverses as the ship consumes more fuel consumption (average 0.28%) in that area. The reason is the wind resistance generated by the Flettner rotor structure causes more fuels consumption which exceed the savings it generated. This indicates clearly that higher the ship speed lower the savings generated by the Flettner rotor.

For route 2a with slower speed, the best season for wind assisted shipping is July, which can lead to 47.76% of saving in fuel consumption, while the worst season is April, but it can still save 14.71% fuel. For the return direction under this speed, the best season is still July, while the worst season turns out to be January, but it still obtains 12.87% fuel savings. The fuel savings of both directions are almost same at an average value of around 25% throughout the whole year.

For route 2a with medium speed, the most favorable season is still July, which can lead to 14.43% of saving in fuel consumption, while January and October become two worst seasons as their fuel savings are both around only 1%. For the return direction with medium speed, the fuel saving caused by Flettner rotors does not change a lot during the whole year at an average value of -6.44% (saving). Both directions have almost same average fuel savings throughout the whole year.

However, for faster speed route 2a, except spring around April, all other seasons are not suitable for shipping with Flettner rotors throughout the year, as it consumes more fuel compared to fully motorised baseline ship due to the added drag. For the route 2b, the situation becomes a little better for faster speed as it can manage only average 1.75% fuel savings. This case study also clearly shows the fuel saving benefits from Flettner rotors highly depend on the random wind conditions in different seasons and the ship speed.

Results for Route 3:

Table 8.4 Fuel consumption saving for Route 3

a) Puerto la Cruz in Venezuela - Gibraltar
b) Gibraltar - Puerto la Cruz in Venezuela

Route/Speed	JAN	APR	JUL	OCT	Average	Combined Annual Average
3a / 6 knots	-10.97%	-6.98%	0.93%	-21.73%	-9.59%	-14.83%
3b / 6 knots	-33.64%	-19.23%	-13.32%	-13.70%	-19.91%	
3a / 10 knots	-7.31%	2.15%	4.00%	-5.16%	-1.58%	-3.18%
3b / 10 knots	-9.75%	-3.89%	-3.47%	-2.00%	-4.76%	
3a / 14 knots	1.98%	3.26%	4.79%	2.57%	3.15%	0.8%
3b / 14 knots	-1.60%	-3.18%	-1.05%	-0.38%	-1.55%	

As can be seen from Table 8.4, shipping area 3 has the same trend as shipping area 1 and 2 that the slower speed will generate more fuel saving than faster speed for the whole year.

For route 3a under slower speed, it is clear that shipping in October obtains most benefits from the Flettner rotor while shipping in July consumes more fuels unexpectedly. For the return direction under this speed, all seasons can lead to relatively large fuel consumption savings. From the aspect of the whole year, the backward direction route can generate 19.91% fuel savings which even double the savings from outward direction route (9.59%).

For route 3a under medium speed, both January and October are appropriate seasons for shipping with the Flettner rotors while April and July are not. For the return direction route (3b) with medium speed, the January is still the best season and all of the other seasons the ship generates lower savings and it can obtain a little more average fuel saving than the outward direction.

For route 3a with faster speed, the whole year is totally unsuitable for using Flettner rotor technology. For route 3b with faster speed, almost all year around the ship can obtain only little fuel saving (-1.55%), which is a bit better than the outward direction of route 3a. This case study still clearly shows the performance of ship fitted with Flettner rotors highly depend on the sailing seasons as different seasons will produce different wind conditions.

Results for Route 4:

Table 8.5 Fuel consumption saving for Route 4

a) Brisbane in Australia - Yokosuka in Japan
b) Yokosuka in Japan - Brisbane in Australia

Route/Speed	JAN	APR	JUL	OCT	Average	Combined Annual Average
4a / 6 knots	-26.73%	-20.61%	-11.51%	-9.31%	-16.92%	-20.23%
4b / 6 knots	-45.07%	-19.09%	-13.39%	-15.51%	-23.55%	
4a / 10 knots	-3.53%	-6.97%	-2.59%	-3.34%	-4.10%	-4.48%
4b / 10 knots	-6.96%	-9.73%	1.43%	-3.85%	-4.86%	
4a / 14 knots	-2.68%	-0.90%	1.21%	0.44%	-0.48%	-0.4%
4b / 14 knots	-0.15%	-2.71%	0.07%	1.50%	-0.32%	

Route 4 has a different characteristic from all other shipping areas as the sailing direction of this route is almost between south and north. As can be seen from Table 8.5, although the sailing directions are totally different, the operation of slower speed can still lead to more fuel savings than faster speed almost all year around.

For route 4a with slower speed, January and April are two good seasons in which the sailing ship can get more than 20% fuel savings and July and October followed with around 10 % savings. For route 4b with slower speed, January becomes the only season when the ship receives huge benefits while other three seasons the ship also has good performance (from 13.3% to 19.09%). The return direction route provides more fuel savings than outward direction route at a slower speed.

For route 4a with medium speed, the average 4.10% fuel saving can be achieved almost a whole year. For route 4b with medium speed, April will be the best season to gain more benefit while July should be avoided as fuel consumption increases.

For route 4a and 4b with faster speed, there is still very little benefit in all seasons with an average saving of 0.4%, so it can be considered sailing with faster speed in route 4 with Flettner rotors is meaningless. Whether the speed is medium or faster, the two opposite directions under same speed have almost same average fuel savings throughout the whole year.

The fuel saving results of this case study are still sensitive to the sailing seasons which do produce different wind conditions.

Results for Route 5:

Table 8.6 Fuel consumption saving for Route 5

a) Banda Aceh at Malacca - Durban in South Africa
b) Durban in South Africa - Banda Aceh at Malacca

Route/Speed	JAN	APR	JUL	OCT	Average	Combined Annual Average
5a / 6 knots	-10.55%	-14.02%	-40.26%	-20.16%	-21.23%	-19.99%
5b / 6 knots	-5.02%	-26.67%	-31.77%	-11.70%	-18.82%	
5a / 10 knots	-1.56%	-0.40%	-6.60%	-6.78%	-3.84%	-4.78%
5b / 10 knots	0.75%	-11.45%	-10.64%	-1.40%	-5.71%	
5a / 14 knots	0.02%	-0.94%	-0.80%	-1.57%	-0.82%	-0.47%
5b / 14 knots	2.17%	-3.59%	-1.96%	2.90%	-0.12%	

As can be seen from Table 8.6, the trend follows the same principle that operating at a slower speed in route 5 can generate more fuel saving than faster speed. For both route 5a and 5b at a slower speed, the most fuel consumption saving happens in July while the least saving happens in January.

For route 5a at medium speed, July and October will be the most appropriate shipping season while for the return direction, the best shipping seasons become April and July.

When the ship has faster speed, the benefit from Flettner rotor is very little in both directions. And for all year around, average fuel savings at the two opposite directions under same speed do not have much difference.

All of above case studies illustrate the performance of ship fitted with Flettner rotors highly depend on the wind speed and directions which will change greatly in different seasons and one principle can be drawn that slower ship speed can lead to more fuel saving benefits from Flettner rotors than higher speed.

8.3.2 Case study 1 - annualised performance

To show more intuitive results towards annualised performance, three figures are produced to compare the savings as well as the combined global average for all the routes combined, which are presented in Figure 8.11, Figure 8.12 and Figure 8.13.

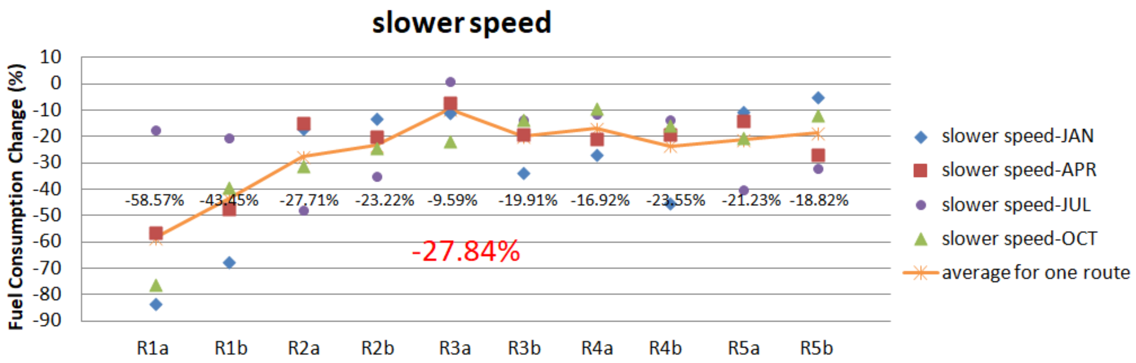


Figure 8.11 Fuel consumption saving percentage under slower speed

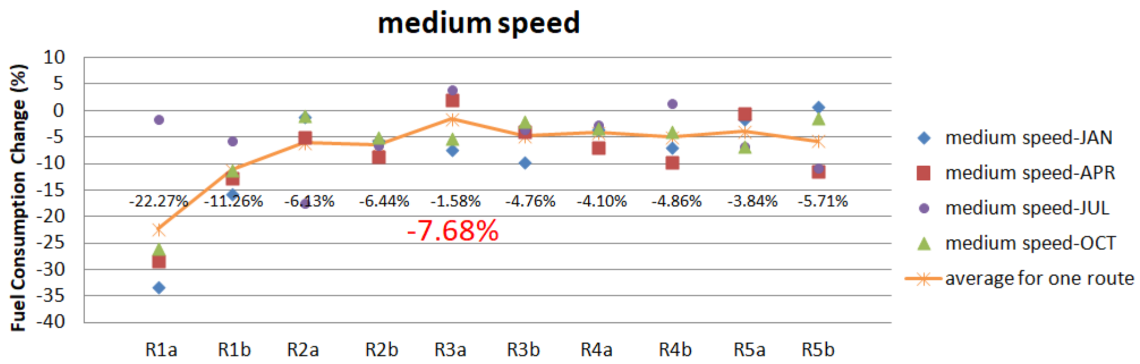


Figure 8.12 Fuel consumption saving percentage under medium speed

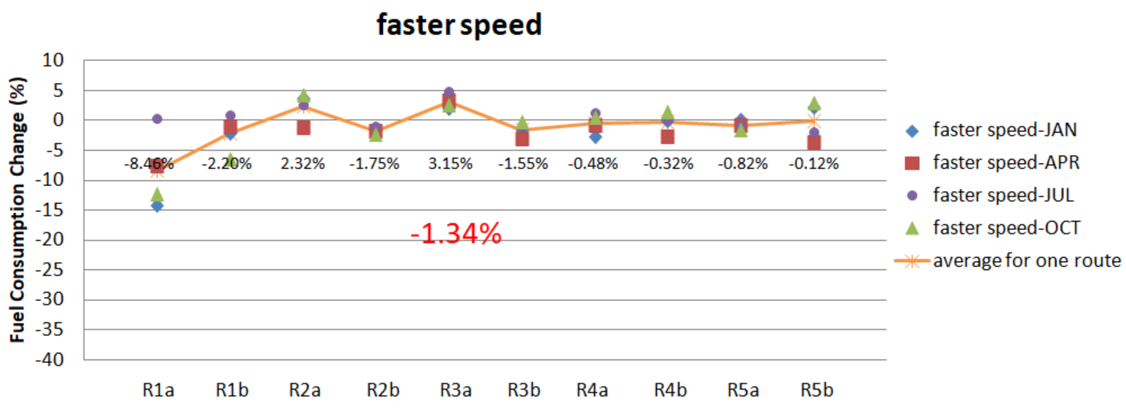


Figure 8.13 Fuel consumption saving percentage under faster speed

From a year-round perspective, taking into account the fuel saving results of the five shipping areas, Figure 8.11, Figure 8.12 and Figure 8.13 show that when the ship is sailing at a slower speed (6 knots), the Flettner rotor technology will bring 27.8% fuel saving to the ship; When the ship is sailing at a medium speed of 10 knots, fuel consumption will be reduced by 7.68%; while when the ship is sailing at a higher speed (14knots), it will only bring a fuel consumption benefit of 1.34% through the installation of Flettner rotors. Combined with the fuel consumption saved on each individual route in the whole year, it can be seen that wherever the ship is sailing in, the operation of slower speed always generates more benefits using the Flettner rotor technology than the faster speed. Average annual fuel consumption saving on each individual route also varies, as can be seen from these figures, sailing along route 1 can save more fuels than other routes, which means that the west-east lines in the Pacific Ocean will be the best shipping area with Flettner rotor technology, while sailing in route 3a (from Puerto la Cruz in Venezuela to Gibraltar) will obtained least fuel saving benefits, especially when the ship sails at higher speed, it even consumed average 3.15% more fuels because of installation of Flettner rotors. When the ship sails on other routes at the same speed, the fuel saving benefits obtained from Flettner rotors are in the middle, and the trend of change is relatively stable. These results are critical, and can provide operators with a reliable reference when making shipping decisions, such as whether to install Flettner rotors on the ship, whether to operate low-speed or high-speed navigation in a certain area, and In which season shipping can be more profitable.

In order to better understand the ship sailing situation, the case route 1a with the departure time of January 5th is taken as the example to show the relevant data in detail. The voyage optimisation model divided this route into 17 stages. The ship speed and relevant wind conditions (wind speed and relative wind angle) recorded in every stage of route 1a departures at 5th January are extracted in Figure 8.14, Figure 8.15 and Figure 8.16.

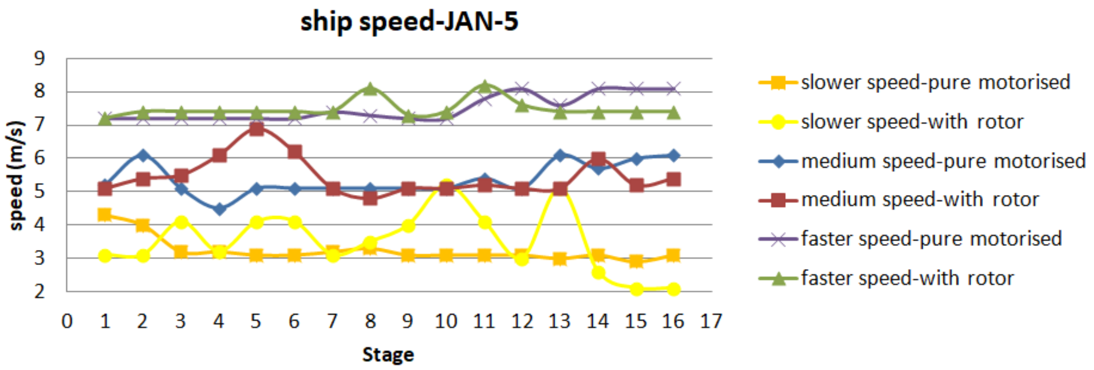


Figure 8.14 Ship speed at each stage of route 1a departure at JAN-5

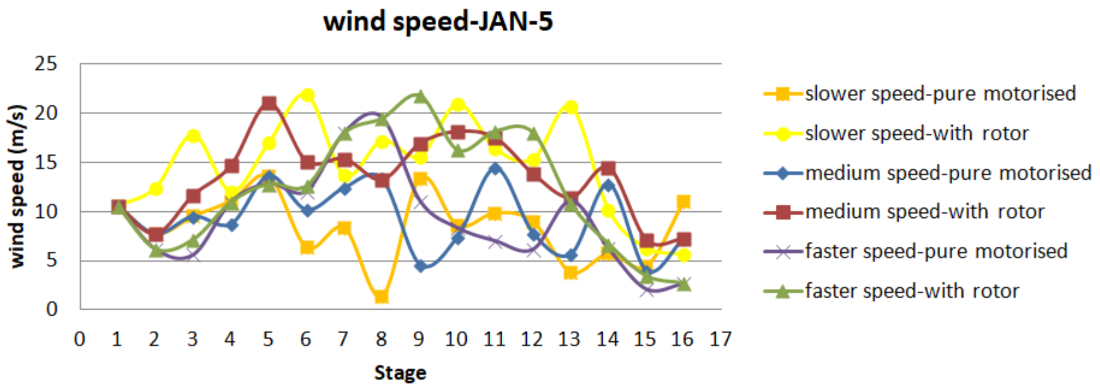


Figure 8.15 Wind speed at each stage of route 1a departure at JAN-5

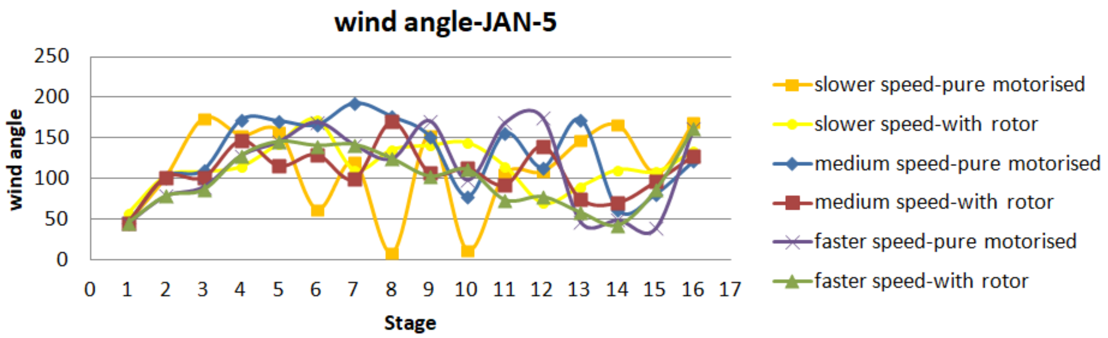


Figure 8.16 Wind angle at each stage of route 1a departure at JAN-5

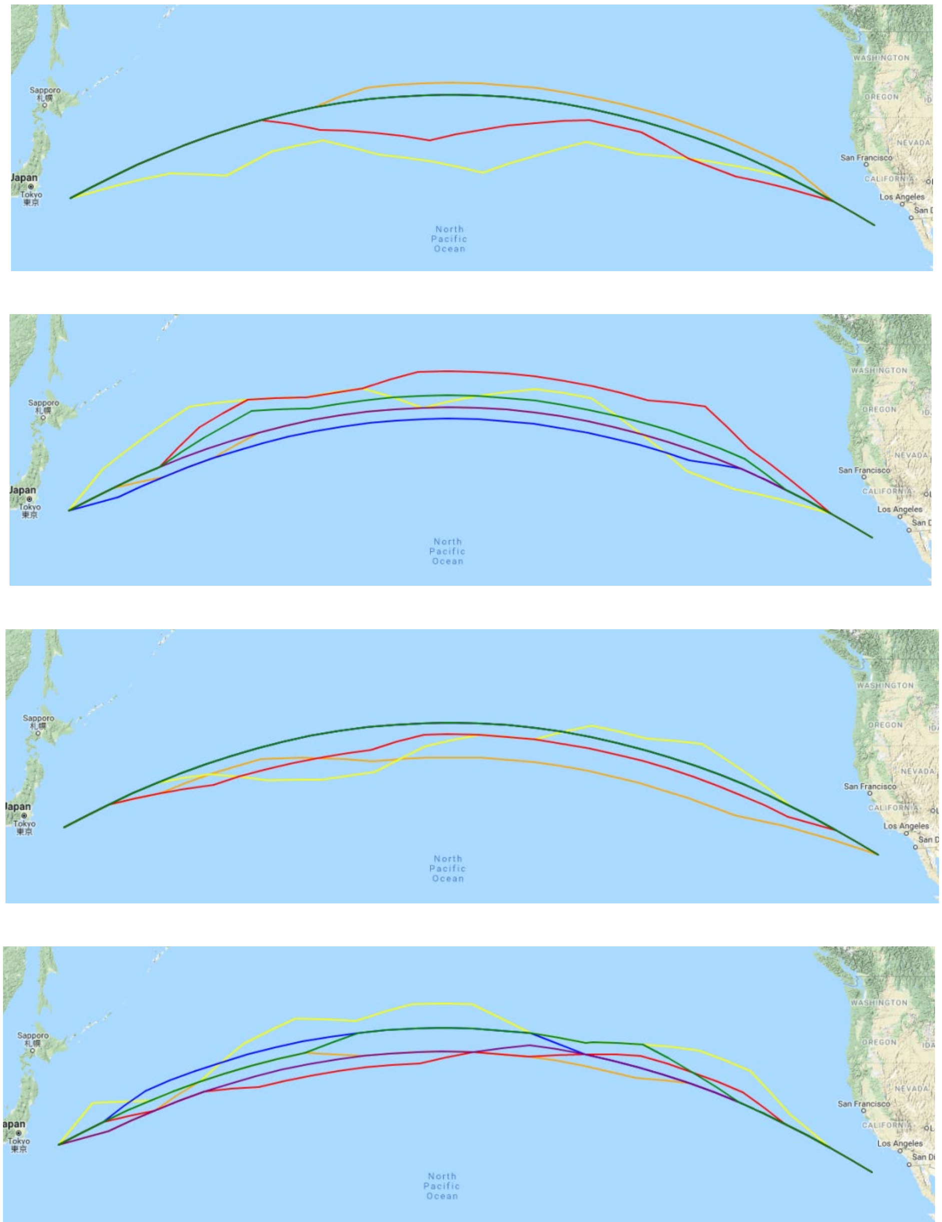
These figures show that the ship speed will change with the local and instant wind conditions as the ship is passing. The ship fitted with Flettner rotor is more willing to chase the sea conditions of higher wind speed in the downwind and beam wind directions for greater fuel efficiency. This once again proves the performance of Flettner rotor propulsion ship highly depends on the wind conditons. It is already known more fuel savings can be obtained from Flettner rotor technology when the ship operates at slow or medium speed. Through these three figures, it can be also clearly seen that the situations of slower and medium speed always corresponds to the fact that the ship speed is slower than the wind speed. So one conclusion can be drawn that, when the ship operates at the speed slower than wind speed, more benefits in terms of energy efficiency can be obtained from Flettner rotor technology.

At last, for the purpose of routes visualisation, all routes generated from the proposed weather routing system under different departure seasons, speed and equipment conditions are drawn on the map as shown in the following figures. These routes all have the highest energy efficiency as they are the routes that consume the least amount of fuel under the corresponding conditions. The map legend is explained in Figure 8.17 in the first place.

Figure 8.17 Map Legend

As can be seen from the following figures, the routes of the ship under different navigation conditions are different. The ship speed, the sailing season and the installation of Flettner rotors will affect the shipping route. The ship will change the route according to the sea conditions, especially if it is equipped with Flettner rotor technology, it will automatically cater for more favorable wind conditions. When the routes change, the fuel saving benefits from Flettner rotors will also change accordingly.

Route 1a visualisation at different departure seasons is shown in Figure 8.18.



(a) January

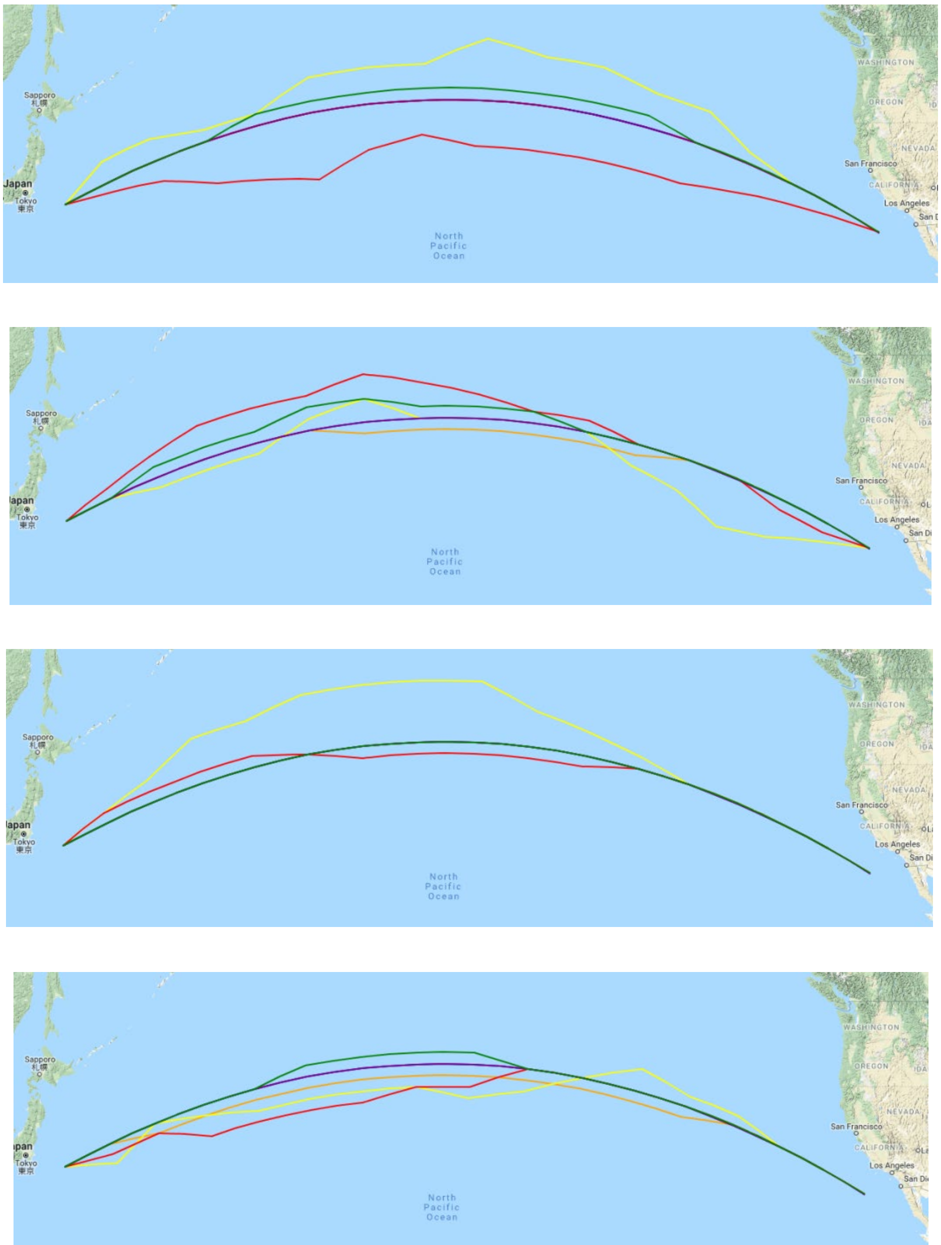
(b) April

(c) July

(d) October

Figure 8.18 Route 1a visualisation (from Chiba in Japan to Los Angeles in the USA) (Map data ©2018 Google)

Route 1b visualisation at departure different seasons is shown in Figure 8.19.



(a) January

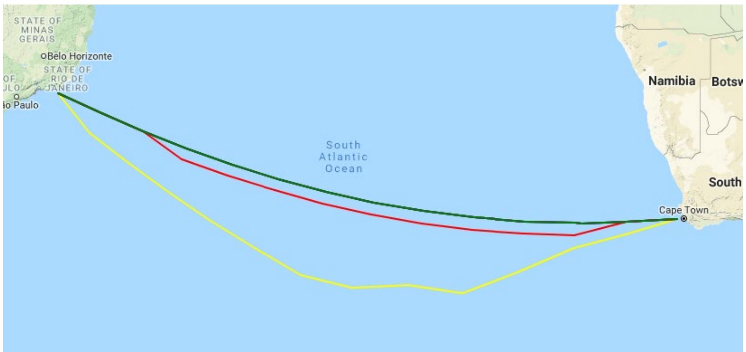
(b) April

(c) July

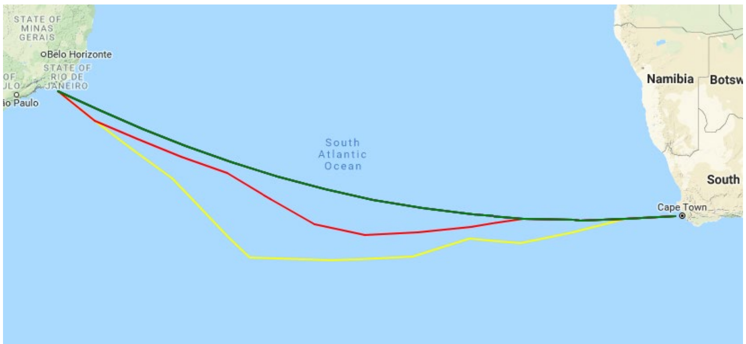
(d) October

Figure 8.19 Route 1b visualisation (from Los Angeles in the USA to Chiba in Japan) (Map data ©2018 Google)

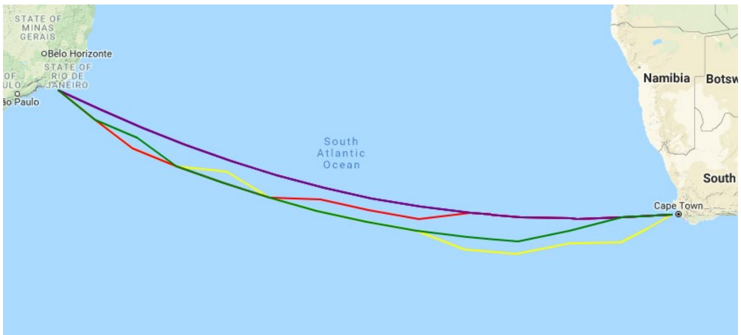
Route 2a visualisation at different departure seasons is shown in Figure 8.20.



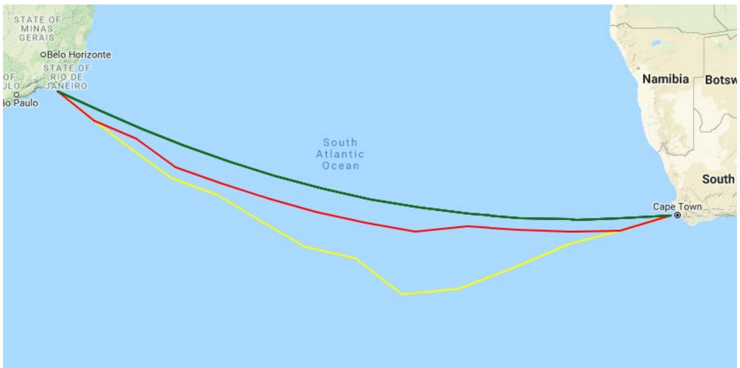
(a) January



(b) April



(c) July

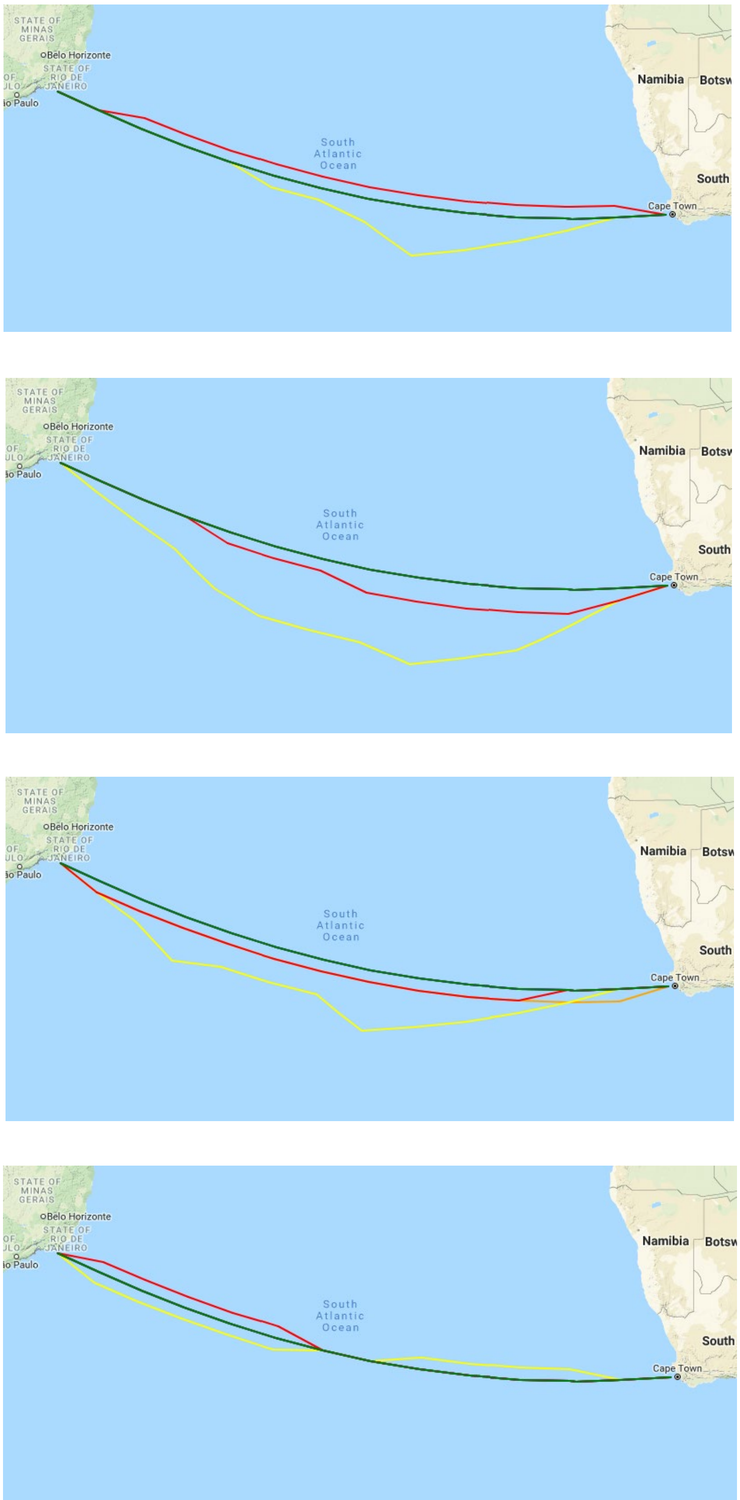


(d) October

Figure 8.20 Route 2a visualisation

(from Rio de Janeiro in Brazil to Cape Town in South Africa) (Map data ©2018 Google)

Route 2b visualisation at different departure seasons is shown in Figure 8.21.



(a) January

(b) April

(c) July

(d) October

Figure 8.21 Route 2b visualisation

(from Cape Town in South Africa to Rio de Janeiro in Brazil) (Map data ©2018 Google)

Route 3a visualisation at different departure seasons is shown in Figure 8.22.

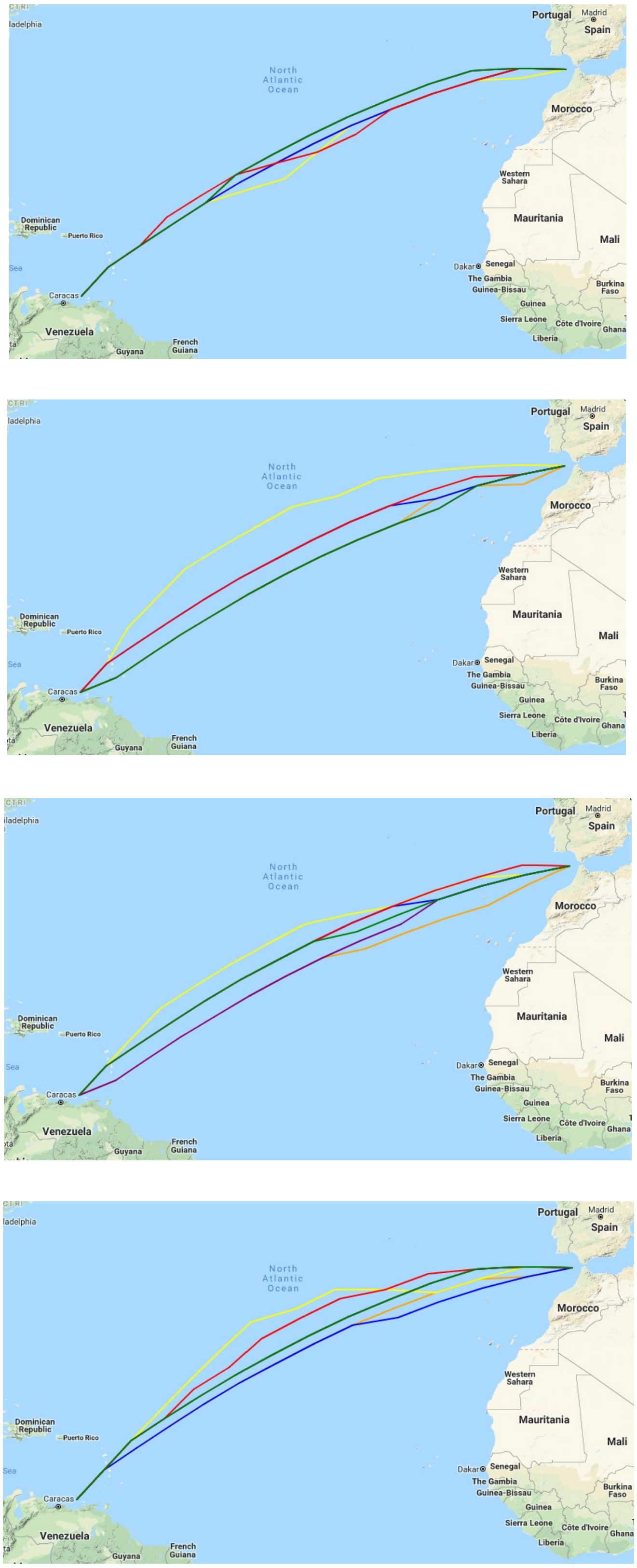


Figure 8.22 Route 3a visualisation (from Puerto la Cruz in Venezuela to Gibraltar) (Map data ©2018 Google)

Route 3b visualisation at different departure seasons is shown in Figure 8.23.

(a) January

(b) April

(c) July

(d) October

Figure 8.23 Route 3b visualisation (from Gibraltar to Puerto la Cruz in Venezuela) (Map data ©2018 Google)

Route 4a visualisation at different departure seasons is shown in Figure 8.24.

(a) January (b) April (c) July (d) October

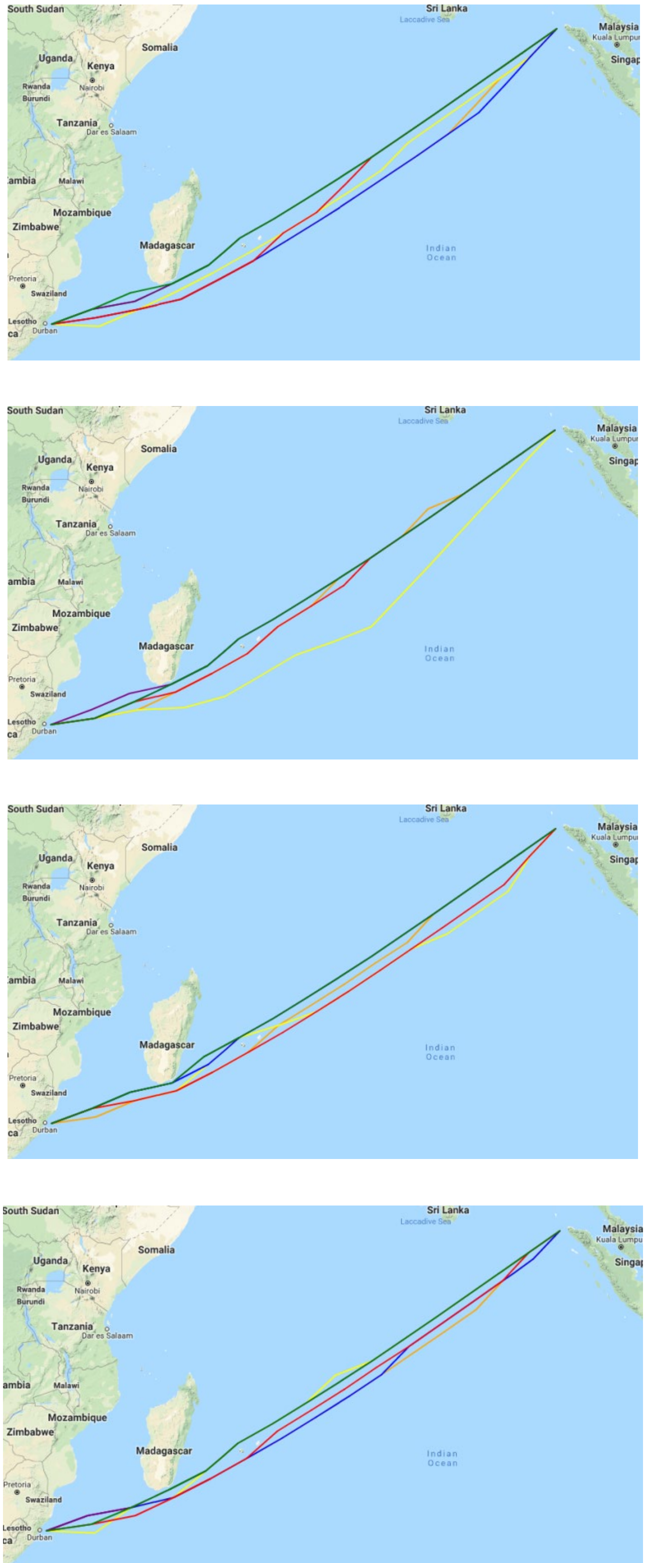
Figure 8.24 Route 4a visualisation (from Brisbane in Australia to Yokosuka in Japan) (Map data ©2018 Google)

Route 4b visualisation at different departure seasons is shown in Figure 8.25.

(a) January (b) April (c) July (d) October

Figure 8.25 Route 4b visualisation (from Yokosuka in Japan to Brisbane in Australia) (Map data ©2018 Google)

Route 5a visualisation at different departure seasons is shown in Figure 8.26.



(a) January

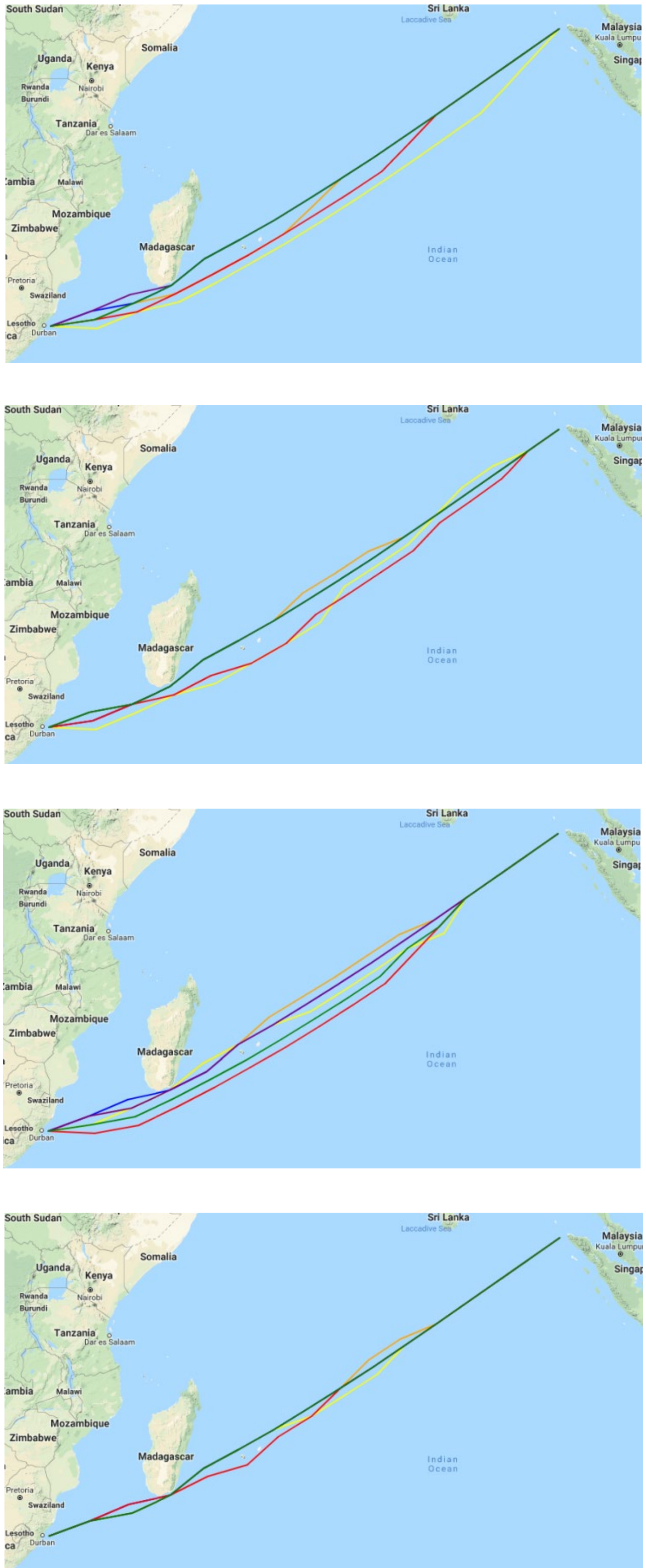
(b) April

(c) July

(d) October

Figure 8.26 Route 5a visualisation
(from Banda Aceh at Malacca to Durban in South Africa) (Map data ©2018 Google)

Route 5b visualisation at different departure seasons is shown in Figure 8.27.



(a) January

(b) April

(c) July

(d) October

Figure 8.27 Route 5b visualisation (from Durban in South Africa to Banda Aceh at Malacca) (Map data ©2018 Google)

8.3.3 Case study 2 - monthly performance

The previous case study selected only one day of each month as the departure time, and the results obtained cannot fully reflect the average fuel saving performance of the entire month. Therefore, in order to further study the influence of the flettner rotor technology on shipping energy efficiency in each month, it is necessary to select more departure time for weather routing simulation in each month. In this section, route 1 (Chiba in Japan - Los Angeles in the USA) will be taken as an example for research.

As it can be seen from the previous case study that when the ship is sailing along Route 1, the ship fitted with Flettner rotors can obtain the maximum fuel saving benefits in January, while it will obtain the smallest benefits in July. As a result, a more in-depth case study is conducted on these two special months on Route 1. Two opposite sailing directions (outward and return) and three different ship speed (slower, medium and faster) are still investigated, by taking into account different departure times. Four different departure times in the most favorable month, January, and four departure times in the least favorable month, July, for Flettner rotor are investigated. Eight departure dates selected are: JAN-05-2014, JAN-12-2014, JAN-19-2014, JAN-26-2014 and JUL-05-2014, JUL-12-2014, JUL-19-2014, JUL-26-2014.

After performing the calculations, all the results are listed in Table 8.7 and Table 8.8, and presented in Figure 8.28 and Figure 8.29.

Table 8.7 Fuel consumption saving for Route 1 in January

Route /Speed	JAN-05	JAN-12	JAN-19	JAN-26	Average
1a / 6 knots	-83.38%	-72.21%	-70.19%	-71.69%	-74.40%
1b / 6 knots	-67.64%	-77.64%	-74.54%	-48.31%	-67.16%
1a / 10 knots	-33.16%	-31.77%	-28.82%	-30.30%	-31.02%
1b / 10 knots	-15.71%	-32.71%	-25.41%	-19.71%	-23.44%
1a / 14 knots	-14.18%	-9.16%	-9.66%	-8.18%	-10.30%
1b / 14 knots	-2.13%	-9.01%	-9.54%	-4.86%	-6.39%

Table 8.8 Fuel consumption saving for Route 1 in July

Route /Speed	JUL-05	JUL-12	JUL-19	JUL-26	Average
1a / 6 knots	-17.30%	-17.03%	-34.96%	-32.28%	-25.40%
1b / 6 knots	-20.20%	-22.87%	-5.50%	-20.12%	-17.23%
1a / 10 knots	-1.64%	0.25%	-6.97%	-4.88%	-3.31%
1b / 10 knots	-5.53%	-2.70%	-0.65%	0.49%	-2.12%
1a / 14 knots	0.26%	0.19%	2.14%	0.03%	0.66%
1b / 14 knots	0.78%	0.14%	1.01%	1.04%	0.74%

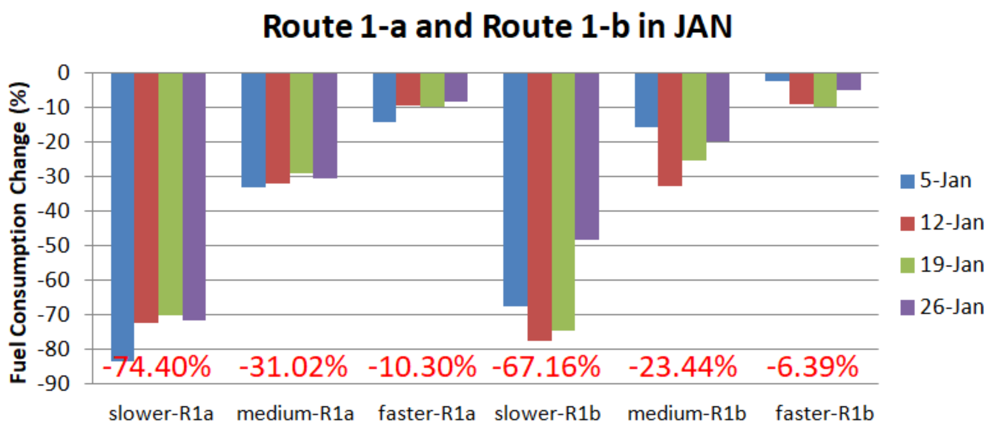


Figure 8.28 Fuel consumption saving percentage in January

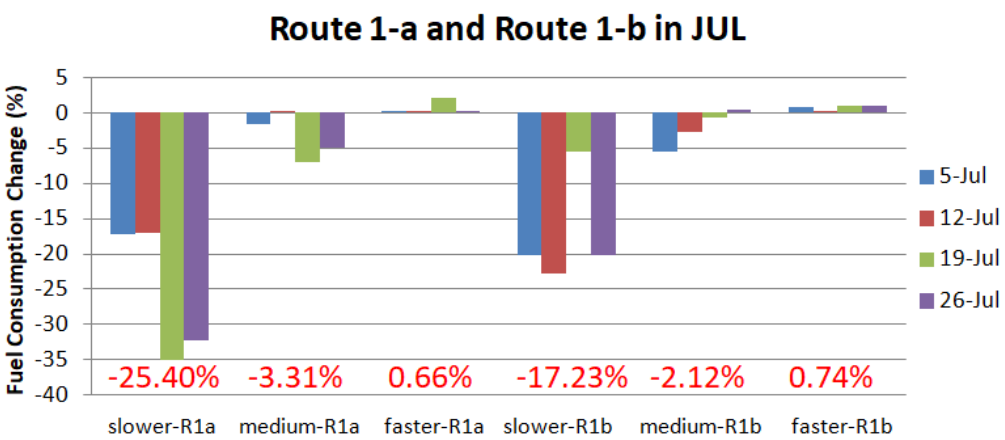


Figure 8.29 Fuel consumption saving percentage in July

As can be seen from Table 8.7 and Figure 8.28, in January, the fuel savings under each speed condition are average, and the fuel saving results of the other three departure days (12th, 19th, 26th) are not much different from those on the 5th. Only when the ship sails on Route 1b at medium speed, the later three departure dates will lead to more fuel savings than the date of 5th. For the general trend in January, route 1a under slower speed still obtains most fuel savings of average 74.40% and return direction under slower speed takes the second place with the value of average 67.16%. Route 1a and 1b under medium speed take the middle places with the value of average 31.02% and 23.44% while route 1a and 1b under faster speed gain least benefits which are average 10.30% and 6.39% respectively. That illustrates January is really suitable for sailing with Flettner rotors in shipping area 1.

As can be seen from Table 8.8 and Figure 8.29, in July, when the ship sails on Route 1a at a slower speed, departing from the dates of 19th and 26th would save nearly twice as much fuel as departing from the dates of 5th and 12th. In other words, under this condition, the second half of the month will bring more fuel saving benefits from Flettner rotors than the first half of the month. When the ship sails on route 1b at slower speed, only the shipping plan with the departure date of 19th will get much less fuel saving benefits than the average. For all other sailing conditions, the results obtained are similar. Sailing under these conditions in July can only obtain very little fuel saving benefits from Flettner rotors technology. From the general trend in July, both directions of Route 1 under slower speed can get good benefits from Flettner rotors with the savings 25.40% and 17.23% respectively. However, besides them, all other sailing conditions lead to very little fuel savings. Route 1a and 1b under medium speed obtain very small benefits which are only 3.31% and 2.12%. When the benefits are examined for the faster speed, all 8 departures in both directions create additional fuel consumption in July. This means the weather in July is only appropriate for ships fitted with Flettner rotors sailing under slower speed. Thus, relative higher speed is not good choices for ship operation in this area.

Based on these simulation results produced by the weather routing system, operators can easily make the decisions about the operational speed, the sailing season selection and whether or not to install Flettner rotors technology towards maximum energy saving and green shipping.

8.3.4 Case study 3 - much higher ship speed

Since one of the main conclusions is that the ship sailing at relatively slower speed can always gain more fuel saving benefits from Flettner rotors compared to the ship with faster speed. Still based on the bulk carrier, another case study which focuses on a much higher speed of 18 knots are carried out as a supplement to prove the obtained conclusion.

The weather routing optimisation still covers all five routes, ten directions and still takes four typical sailing seasons - JAN, APR, JUL and OCT into account. After the weather routing calculation based on the proposed system, the fuel consumption savings from Flettner rotors for all routes at the speed of 18knots in different seasons are shown in Table 8.9 and Figure 8.30, which also show the average fuel savings of the whole year, combined annual average fuel savings of each route and the total fuel savings for all these case studies.

Table 8.9 Fuel consumption saving for all routes at the speed of 18 knots

Route	JAN	APR	JUL	OCT	Average	Combined Annual Average
1a	-2.50%	-3.58%	0.60%	-5.88%	-2.84%	-1.24%
1b	0.26%	0.31%	1.83%	-1.12%	0.32%	
2a	3.55%	0.44%	1.72%	4.04%	2.44%	1.37%
2b	-0.59%	1.22%	0.37%	0.19%	0.30%	
3a	3.40%	3.64%	3.95%	2.05%	3.26%	2.06%
3b	0.22%	0.27%	1.47%	1.41%	0.84%	
4a	1.15%	1.26%	1.25%	1.18%	1.21%	1.11%
4b	-1.24%	-1.38%	1.96%	4.63%	1.01%	
5a	1.12%	1.04%	1.02%	0.06%	0.81%	1.21%
5b	3.15%	-0.16%	1.32%	2.14%	1.62%	

*Total fuel savings is 0.74%

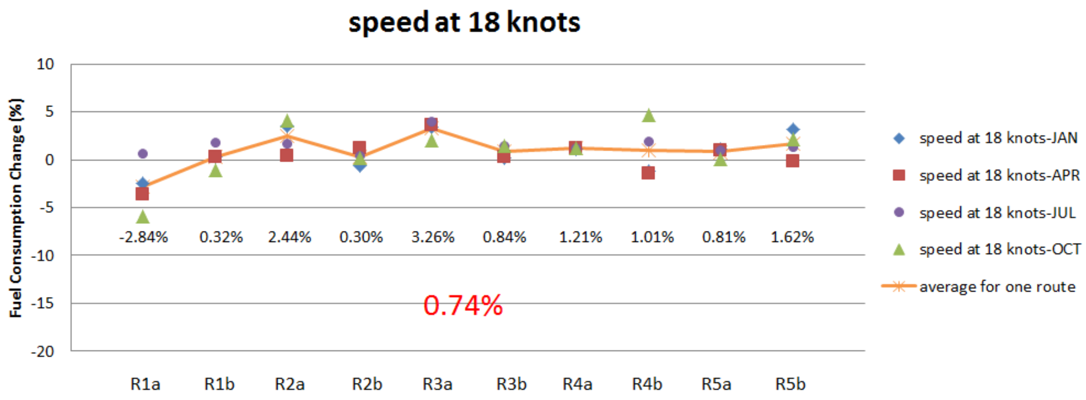


Figure 8.30 Fuel consumption saving percentage at the speed of 18 knots

As can be seen from Table 8.9 and Figure 8.30, except for route1a, the ship does not receive too much fuel saving benefits from the Flettner rotor technology when sailing on all other routes and seasons. Instead, it always consumes more fuel in these scenarios. Even for route 1a, which should have received the greatest fuel saving benefits, it only reaches 5.88% fuel savings in October, which is already the largest value that can be obtained in all case studies. In January and April, the fuel savings values are only 2.50% and 3.58% respectively. In July, it even consumed 0.60% more fuels. These lead to the average annual saving was only 2.84%. For all other routes, from a year-round perspective, the ship fitted with Flettner rotors consumes more fuels than pure motorised propulsion mode, ranging from 0.30% to 3.26%. Considering all the routes and the total fuels for the whole year, the ship consumes 0.74% more fuels after installation of Flettner rotors. Compared to the ship sailing with the speed of 14 knots, which can obtain at least 1.34% fuel saving benefit from Flettner rotors technology, the ship which sails at the speed of 18 knots can no longer received the benefits from Flettner rotors to improve its energy efficiency. This also verifies the previous conclusions.

Furthermore, the case studies which focus on route 1 at the speed of 18 knots are carried out for different departure dates as well. The weather routing simulations still pay attention to the most favorable month January and the least favorable month July according to the previous conclusion. The departure dates are still respectively JAN-05-2014, JAN-12-2014, JAN-19-2014, JAN-26-2014 and JUL-05-2014, JUL-12-2014, JUL-19-2014, JUL-26-2014. The fuels saving results are listed in Table 8.10 and Table 8.11 and presented in Figure 8.31 and Figure 8.32.

Table 8.10 Fuel consumption saving for Route 1 in January

Route /Speed	JAN-05	JAN-12	JAN-19	JAN-26	Average
1a / 18 knots	-2.50%	-6.88%	-5.72%	-2.58%	-4.43%
1b / 18 knots	0.26%	-2.96%	-1.71%	-2.40%	-1.70%

Table 8.11 Fuel consumption saving for Route 1 in July

Route /Speed	JUL-05	JUL-12	JUL-19	JUL-26	Average
1a / 18 knots	0.60%	0.86%	2.10%	0.79%	1.09%
1b / 18 knots	1.83%	0.00%	1.87%	2.69%	1.60%

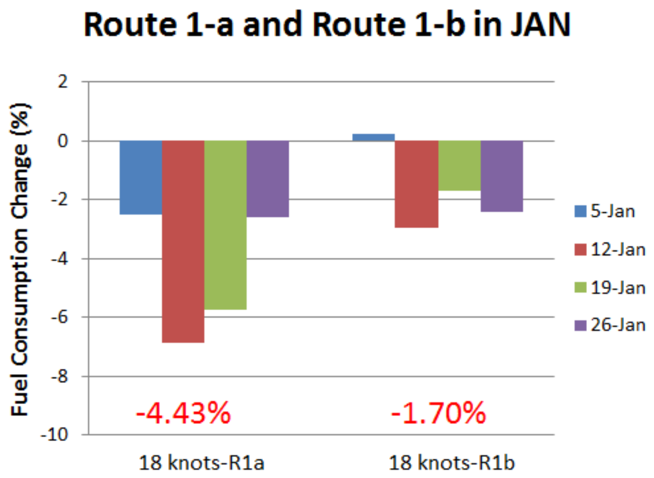


Figure 8.31 Fuel consumption saving percentage in January at the speed of 18 knots

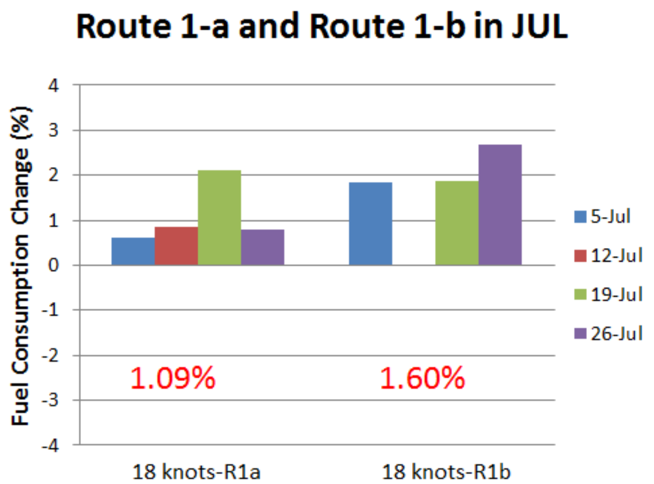


Figure 8.32 Fuel consumption saving percentage in July at the speed of 18 knots

As can be seen in Figure 8.31, for route 1a, when the ship is sailing at 18 knots, an average of 4.43% fuel savings can be obtained from Flettner rotors technology throughout January. This seems to be a good result, but compared with case study 2, in which the 10.30% average fuel saving can be achieved when the ship speed is 14 knots, the fuel saving benefits at 18 knots fell significantly. For route 1b, the average fuel saving value throughout January is 1.70%, which is also much lower than the average fuel saving value of 6.39% for the ship sailing at 14 knots. It can be seen that increasing the ship speed will indeed reduce the fuel savings benefits from the Flettner rotors.

As can be seen in Figure 8.32, for both directions of route 1, when the ship fitted with Flettner rotors sails at the speed of 18 knots in July, it consumes 1.09% and 1.60% more fuel respectively than the pure motorised ship. However, according to Figure 8.29, when the ship speed is 14 knots, the two corresponding results are 0.66% and 0.74%. This means when the ship speed is increased to 18 knots, the proportion of additional fuel consumption is further increased. This once again proves the previous conclusion: The higher the ship speed, the less fuel is saved by Flettner rotors. When the ship speed rises to certain degree, Flettner rotors will even cause the ship to consume more fuel.

8.4 Conclusion

This chapter presents the application of the methodology on how detailed performance analysis of a ship fitted with Flettner rotors should be performed. Based on the proposed weather routing system, many case studies are carried out on a motorised ship with and without Flettner rotors. According to results, it can be seen that the ship fuel consumption performance varies with different sailing conditions including various shipping routes, departure times and ship speeds. One principle result extracted from the results is that, without considering other conditions, the ship sailing at relatively slower speed can always generate more fuel saving benefits than faster speed. What is more, when the ship operates at the speed slower than wind speed, more benefits in terms of energy efficiency can be obtained from Flettner rotor technology. Besides, the west-east lines in the Pacific Ocean can be regarded as the best shipping routes with Flettner rotor technology among all the case studies, while sailing from Puerto la Cruz in Venezuela to Gibraltar will obtained least fuel saving benefits. This study can offer some reference value for shipping industry for the research on the application of Flettner rotors to shipping.

The main conclusion is that the performance of ship fitted with wind assist technologies should be calculated based on annualised fuel savings rather than focusing on individual voyages. This is due to the fact that, the performance of the ship with wind assist technologies heavily depends on the wind magnitude and directions, which are random by nature and the time of sailing. Therefore, many calculations should be carried out on different dates, times and directions to determine the average annualised performance of the ship fitted with wind assist technologies in a given route. Due to the wind magnitude and direction, not all routes are feasible for ships with wind assist technologies, and therefore, investments by shipping companies should be based on the scientific analysis to avoid any disappointment.

The study in this chapter also reflects the effectiveness of the proposed system. The system has several significant benefits: It can fit well with newly introduced technologies; it can fully reflect the impact of weather conditions on shipping; it can accurately simulate almost all routes worldwide, all sailing seasons, and any ship speed allowed; it has high computational efficiency and can support relatively large quantities of calculations such as annual calculations and cross-regional calculations. These benefits have practical significance for decision makers, shipping companies and even ship designers. They can select the route, ship speed, sailing time and energy-saving technologies based on the predicted results to gain more profits. For example, the system can support the decision makers to determine the best route for a given wind assist technology or even select the best technology for a given route.

At last, based on all above analysis, together with some personal thoughts, a framework is proposed for assessing the performance of wind assist technology which is shown as below:

STEP 1: Identify the operating area (Route(s));

STEP 2: Determine the operating profile of the ship including min and max operating speed range;

STEP 3: Check whether average annual wind speed is greater than the ship speed. Wind assist technologies highly sensitive to wind speed and the wind direction;

STEP 4: Calculate the annualised average saving by simulating a number of voyages at different times of the year including return legs of the journeys;

STEP 5: If the gain is acceptable please utilise weather routing approaches to extract maximum benefits - especially at lower average speeds;

STEP 6: Perform similar analysis for different speeds around the ideal operating speed to weigh the gains and losses;

STEP 7: Results should be provided in terms of net fuel saving.

As the system is very versatile, same steps can be repeated for other wind assist technologies. Different technologies will definitely have different performance, which may have a significant impact on shipping.

9 Conclusions and Future Work

9.1 General discussion

This thesis mainly introduces the development of a ship weather routing system towards energy efficient shipping and studies the voyage performance of ship fitted with Flettner Rotors. The main works and discussions are:

1. The significance and development of voyage optimisation are reviewed, especially the progress of speed optimisation is reviewed in detail. The applied algorithms for weather routing are exhaustively summarised. These classic algorithms include Calculus of variations, Isochrone method, Isopone method, Dynamic programming method, Dijkstra's method, DIRECT method and Evolutionary methods. Many popular ship routing services are introduced as well. At last, the development of wind assist technologies is also reviewed, including Flettner rotor technology, kite technology and Dyna Rig technology. Among them, Flettner rotor technology is reviewed with emphasis. The limitations of these researches are pointed out, and the proposed weather routing system, which will try to address them is presented.

2. The elements that must be considered for a typical ship weather routing system are summarised, including various ship performances calculation and external environmental data. Holtrop 1984 method is selected for ship calm water resistance calculation; A modified Kwon's method and a combined numerical method of Gerritsma & Beukelman’s method and Faltinsen’s asymptotic method is selected for the calculation of added resistance due to waves and winds; NORDFORSK (1987) criteria is selected as the ship navigation criterion for ship seakeeping performance calculation to guarantee the ship safety. All these adopted methods can provide the calculation results with adequate accuracy for the corresponding ship performance. These can be realised by empirical formulas or by hydrodynamic software, so that the ship performances can be directly and efficiently calculated.

3. The structure of the ship weather routing which consists of six modules is proposed. Six modules are summarised below:

Ship performance calculation module: All related ship performances calculation will be carried out in this module. According to a certain calculation flow, these performances will be also calculated to finally obtain the main objective performance - fuel consumption, which is regarded as the only indicator to measure the energy efficiency of ships in this study.

Grids system design module: This module aims to distribute a group of networked waypoints in advance for leading the ship travel. The design principles of the grid system are introduced, in which the waypoints are arranged in a parallel manner. An intelligent land avoidance function is developed based on the introduction of GSHHG database so that the weather routing system can cover almost of all the navigation area in the world.

Weather data module: The processing of weather data files is performed in this module, which includes the acquisition and decoding of weather data. A 36 years (1979-2014) global historical weather database is stored in this module as a support for subsequent weather routing calculations. The system can predict the voyage plan for the current shipping task based on the past weather data.

Ship safety module: This module is designed to guarantee the ship navigation safety through ship seakeeping performance calculation. The introduction of ship safety as a constraint when calculating shipping energy efficiency can make the results more reliable. Moreover, the calculation of the ship safety has not been simplified, but four representative seakeeping parameters have been selected in the NORDFORSK (1987) criteria: the probability of slamming, the probability of deck wetness, RMS of roll and RMS of vertical acceleration at FP. It is only when all the four parameters meet the safety conditions that it can be determined that the ship is safe under this condition.

Weather routing module: As the core module of the system, the optimisation of voyage plans is performed in it. A Pareto front (ETA vs fuel consumption) will be generated in final destination waypoint, which means that the system will provide a corresponding minimum fuel consumption voyage plan for any ETA pre-set by the user. A combination of global and local optimisation algorithm is adopted, which can calculate all possible voyage plans within a reasonable range. The algorithm only considers two optimisation variables (ship speed and heading) and focuses on two results (ETA and fuel consumption). The algorithm acheves automatic voyage optimisation and allows the system to fully consider the weather's impact on shipping. The system can consider the speed according to the local weather during the journey and make the optimal voyage plan from the global level with the adopted weather routing algorithm. Besides, based on this module, calculations for other types of optimal routes can also be implemented, like safest route etc.

Post-processing module: The post-processing of the result is performed in this module. A backward iteration algorithm is adopted to extract the navigation information of the optimal voyage plan, including sailing time, fuel consumption, speed, the position of the passing waypoints, and weather data etc., and visualisation of result routes is also implemented in this module. So once a set of optimal results are determined by the user, their all relevant information will be provided and the route will be clearly shown on the map.

All these six modules constitute the basic framework of the system, so that the system has the basic elements of a typical weather routing system. Every module plays an important role in the system, and the connection of them makes the system complete the shipping simulation smoothly.

A 115K DWT Crude Oil Tanker sailing along different real routes is taken as a case study to preliminarily validate the proposed weather routing system. By comparing with the sea trial data of the ship, the validation results show the predicted ship brake power performance in calm water is only average from 1.01% to 3.13% under different loading conditions. The recorded data of a more repeated real route between Freeport (Texas) and Puerto la Cruz in noon report is also introduced for FCR performance comparison. The results show that the difference between most of simulated and recorded results are acceptable, and the simulative FCR results have a good response to weather conditions and perform a better increasing trend with the speed increased. The ship sailing in the Pacific Ocean is also selected for the fuel consumption performance validation. The results show the simulative fuel consumption values are generally smaller than the record value within a reasonable range, and the fuel consumption performance on each stage of the voyage calculated by numerical method and modified Kwon's method has a very good response to the weather conditions and ship speeds. The differences of weather data from different sources are also checked. A global optimisation is performed for this real route and the results show that the global weather routing optimisation can provide the ship more reasonable voyage plan according to local weather conditions and can make the ship consume 12.95% less fuel than the recorded route at the same ETA of 392 hours. In addition, the results also show that the difference in the minimum fuel consumption under different ETA is large. In this case study, if the difference in ETA is 41.27%, the fuel consumption will differ by 182.72%. Ship safety indicators are also checked and all of them meet NORDFORSK (1987) criteria. The validation procedure proves all the integrated modules work well. All the results show the proposed system can provide users reasonable ship operational strategy towards high energy efficiency.

4. Seven methods are designed for this system to improve its computational efficiency, including create ship performance database, redefine ship travel principle and adjust the grids system scale, merge ship safety module to ship performance prediction module, delete results in every waypoint which cannot meet the time schedule, set the speed control parameter, delete results in every waypoint which cannot meet expected fuel consumption and optimise programming codes. Among them, the creation of a new ship performance database also makes the ship weather routing system combined with other newly introduced technologies very versatile and more efficient. These methods not only reduce the computational cost that makes the system more practical but also make the system structure simpler and the operation logic more reasonable.

A 35,500DWT Bulk Carrier sailing in the North Atlantic Ocean is taken as a case study to demonstrate the effectiveness of these methods. The results show that these methods not only do not affect the optimal results, but also increase the working efficiency of the system by 35 times.

5. Two case studies were carried out to formally verify the proposed weather routing system.

The first case study still takes the scenario of a 35,500DWT Bulk Carrier sailing in the North Atlantic Ocean. The results show that the weather routing system can effectively predict the ship's response to different weather conditions. When a ship encounters a severe sea state, it will reduce the speed to cope with unfavorable weather conditions, and when the ship encounters mild weather, it will perform faster sailing. The ETA ranges from 224 h to 230 h, while the corresponding fuel consumption ranges from 134.78 tonnes to 145.34 tonnes. It can be found that if the ETA is delayed by 3 hours, the shipping can save 4.2% fuels, and when the ETA is further extended by six hours, 7.27% fuels will be saved.

The second case study investigates the scenario of this 35,500DWT Bulk Carrier sailing from Dubai to the middle of the India Ocean. The results show that only the speed optimisation on a fixed route will provide 1.47% fuel savings, while global optimisation can provide 1.60% fuel savings. It can be also found that 3% shorter ETA will consume 4.43% more fuels, 3% longer ETA will generate 7.05% fuel savings and 5% longer ETA will generate 10.2% fuel savings. In addition, changes in the season will lead to changes in the results. Because different seasons have different weather conditions, the corresponding voyage plan and fuel consumption will also change accordingly.

6. The impact of a wind assist technology, Flettner rotor technology, on shipping energy efficiency is studied and a framework is proposed for assessing the performance of wind assist technology. In this part, many case studies are carried out based on a motorised ship with and without Flettner rotors. Various sailing conditions including different shipping routes, departure times and ship speeds are taken into account. The results show that the shipping energy efficiency varies with different sailing conditions. Several conclusions can be extracted that the ship sailing at relatively slower speed can always generate more fuel saving benefits than faster speed; more fuel saving benefits can be obtained from Flettner rotor technology when the ship operates at the speed slower than wind speed; Besides, the west-east lines in the Pacific Ocean would be the most favorable route for the ship fitted with Flettner rotors among all the case studies, while sailing from Puerto la Cruz in Venezuela to Gibraltar will obtained least fuel saving benefits from a year-round perspective.

The results from these representative case studies reflect that this system can provide users with a reliable energy-saving voyage plan. It can provide a good reference for decision makers.

9.2 Conclusion

The main conclusions drawn from this study are:

1. The proposed weather routing has complete functions and can simulate various ships and shipping scenarios including almost all the routes worldwide, all the sailing seasons, all the ship speed sets allowed. It also provides interfaces for newly introduced energy-saving technologies. It can fully consider the impact of weather on shipping and can efficiently calculate the optimal voyage plan towards energy efficiency.

2. Compared to pure speed optimisation, global optimisation can provide better voyage plan towards energy efficiency.

3. Different sailing conditions lead to different voyage plans and different fuel consumption. Therefore, decision makers, shipping companies and even ship designers should select the route, ship speed, sailing time and energy-saving technologies carefully based on the predicted results to gain more profits.

4. A slight adjustment to ETA will have a measurable impact on the final fuel consumption. Shortening ETA will increase fuel consumption, while extending ETA will reduce fuel consumption. The operators can determine the ETA in advance before the ship leaves the port, and reduce the fuel consumption as much as possible to increase profits without violating the contract. They can also negotiate and sign a contract with the cargo owner according to the predicted relationship between ETA and fuel consumption.

5. The ship sailing at relatively slower speed can always generate more fuel saving benefits using Flettner rotor technology than faster speed. One way to judge whether the speed is slow or fast is to check if the ship speed is lower than the wind speed. The ship will always achieve good fuel saving performance through Flettner rotors when sailing at speeds lower than wind speeds

6. The performance of ship fitted with wind assist technologies should be calculated based on annualised fuel savings rather than focusing on individual voyages. Because the performance of the ship with wind assist technologies heavily depends on the wind magnitude and directions, which are random by nature and sailing

seasons. Therefore, many calculations should be carried out on different dates, times and directions to determine the average annualised performance of the ship fitted with wind assist technologies in a given route.

Finally, this weather routing system can be used towards:

1. Helping industry and academia understand the internal mechanisms of interaction of weather conditions, ship systems, ship response, energy efficiency and other factors in the shipping process.

2. Developing energy efficient ship operations strategies for shipping companies and can be used for fleet level optimisation.

3. Training crew to understand the effect of environment on ship energy performance and develop weather routing or voyage optimisation.

4. Assessment of various technologies and operational practices on ship performance for the individual voyage and even annualised operations.

9.3 Main contributions and novelties

The main contributions and novelties of the study are re-emphasised here, they are:

1. The system achieves automatic speed optimisation. The system can calculate all the speed options automatically within the allowable range, and then determine the speed operation plan through optimisation.

2. The system integrates various empirical and numerical computation methods for multiple ship performances calculation, which can fully reflect the weather's impact on shipping. The system can provide accurate ship operations with various weather conditions.

3. By integrating the 36-year history weather database, the system can make voyage plans based on past weather data before the ship departure. Because the weather in the ocean changes little every year, the voyage plan predicted based on past weather data can serve as a good reference. Even if the ship receives new weather forecast data during the journey, the system can adjust the voyage plan in time.

4. An Intelligent method to design the grids system is developed, including intelligent land avoidance function, which makes the designed grids system can meet almost all shipping routes in the world. The system can automatically generate the suitable grids system only by entering the position of the departure point and destination point, as well as the required waypoints resolution.

5. A combination of global and local optimisation algorithm is developed as the weather routing strategy of the system. This algorithm improves the system's computational efficiency while achieving automatic optimisation of speed and direction. The system can not only obtain the global optimal solution, but also obtain the local optimal solution for each path point.

6. The proposed approach and the developed tool provide the optimum energy efficient route while taking into account safety to make sure that energy efficient routes do not create unsafe conditions.

7. A series of methods are designed to improve the system's working efficiency and make the system more versatile. The system can be easily combined with various shipping energy-saving technologies. So when new technology is introduced, the system can carry out the corresponding weather routing optimisation based on user's requirements and assess the benefit of the new technology towards energy efficiency.

8. Based on the proposed weather routing system, the impact of wind assist technology 'Flettner Rotors' on fuel consumption of ship is studied as a case study. A framework for assessing the performance of wind assist technology is proposed.

9.4 Suggestions and future work

Due to the limited research period, it is inevitable to introduce some assumptions and simplify some calculation and conditions for the development of the system. Based on these limitations and development trend of the weather routing system, some suggestions for further work are suggested as below:

1. Ship performance calculation is crucial to the final results obtained by the weather routing system. In this study, many estimation formulae and numerical calculation methods have been introduced for the sake of efficiency. Instead, more accurate ship performance can be obtained by experiment in towing tank for each special ship type.

Or when the system is running onboard, users can install appropriate performance testing devices for the ship to better monitor the ship real-time resistance, seakeeping and propulsion performance.

2. This study once discussed the impact of ocean currents on shipping, but ultimately it has to be abandoned because a method that can accurately predict the currents influence has not been achieved. Besides, the system does not consider the ship motion and trim condition etc. during voyage. They need to be carefully studied and taken into consideration by the system in the future.

3. Fouling, which affect the performance of the ship much, should be considered in the proposed system. Actually, as an important factor, fouling has been studied in detail by other PhD students in the SCC project (Lu, 2016). Since the proposed system aims to provide shipping reference for decision makers before ship departure, fouling is not considered at the moment. But it should be added in the system for more accurate ship performance prediction in the future. Besides, hull or propeller damage and aging should also be considered.

4. When considering energy consumption, not only the energy consumption required by the ship to overcome resistance is considered, but also the fuel consumption for various equipment operation and crews' daily life onboard should be considered according to the actual situation.

5. In this system, routes still heavily depend on grids system. Although the grids system is automatically generated, the waypoints resolution of grids system are still manually entered by the user. Therefore, a more intelligent grids system needs to be developed, even an idea can be realised that the system does not require a grids system to plan a route. More perfect land avoidance functions should be further developed.

6. A more efficient optimisation algorithm can be introduced in weather routing module to reduce the calculation time further.

7. When conditions permit, the research on weather routing with other different optimisation goals can be carried out, such as the safest route, the route with average minimum wave heights or the route most suitable for wind propulsion.

8. The program can be packaged into industry standard software that can be installed on the shore or on board, and a vivid interface can be created for the software.

9. One view on the future development of weather routing is to introduce machine learning and big data theory. Introducing these theories can abandon traditional optimisation algorithms and perform weather routing calculations from a new perspective. A simple idea at the moment is to realise that, the system can learn some rules according to recorded navigation information and corresponding historical weather data, and then generate an optimal voyage plan based on the new weather forecast data.

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