# Vessel Routing as an Application of the Shortest Path Problem

## Seminar Routing

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# 1 Introduction

This paper presents different approaches of vessel routing techniques and their possible algorithmic implementation. Also important restrictions and objectives are considered. Afterwards an existing software solution is presented. The paper was created in context of seminar "Routing", supported by Prof. Dr. Sebastian Iwanowski, at University of Applied Science "FH Wedel". In addition Carsten Bullemer, founder of Maritime Data Systems and vesseltracker.com, supported this work with helpful information.

# 2 Classification

When it comes to determining a route, there are several issues that are similar to each other.

There are two general types of problems. The inventory routing problem and the cargo routing problem. [6, p.2] As the name of this paper suggests, we are going to focus on the inventory routing problem. Within this group a distinction is made between whether the visiting order of the nodes (e.g. a port) has to be found or if it's already given.

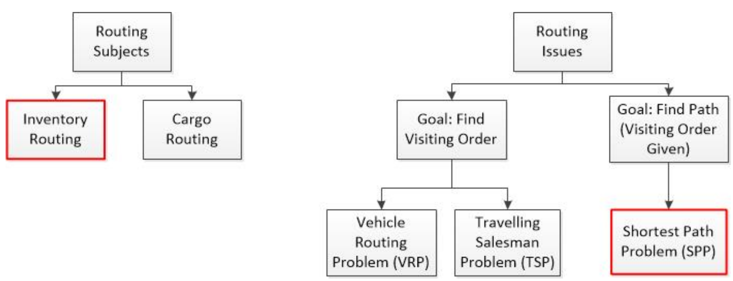


Figure 1: Classification of Routing Issues

If the visiting order should be determined, a further distinction is made between the traveling salesman problem (TSP) and the vehicle routing problem (VRP), where the VRP is a generalisation of the TSP. Their objective is to find the shortest route between a given list of cities and therefore to determine the best visiting order while it is ensured every city has been visited exactly once. In contrast to the VRP the TSP only considers one vehicle and does not take into account any further circumstances or restrictions like customer's demand or vehicle's payload limit.[2, p.5] These problems are NP-complete.

The second kind of problem is to determine the shortest route between two ore more cities in a given order. It is called the shortest path problem (SPP).

In the following, the vessel routing issue is considered as an application of the SPP. The focus is set on finding a possible route or to determine the best possible route for a single vessel between two ports. Therefore we have to consider specific restrictions for the mode of transport "ship".

# 3 Restrictions and Objectives

There are different types of restrictions that should be taken into account while calculating a route for a certain vessel. In some cases complying with this restriction is mandatory to ensure safe operations.

**Restrictions and Factors to be considered:**

- Nautical Restrictions e.g. draught, height, breadth, length of the vessel
- Weather e.g. waves, tide, currents and wind
- Legal Restrictions e.g. SECA, Traffic Separation Schemes
- Security Restrictions e.g. pirate areas or battle zones
- Cost e.g. charter costs, crew wages, fuel costs, toll

Beside the restrictions, there are several objectives a route can be optimized for.

**Relevant Objectives are:**

- Cost
- Distance
- Time
- Ecology

# 4 Weather Routing

Weather Routing is evolving. That's why there are old fashioned and progressive weather routing approaches. Traditional weather routing systems rely on the principle of storm avoidance. Whereas modern weather routing systems make use of various input factors and weigh up between them. Both are available as shore-based and on-board systems as well.

## 4.1 Traditional Weather Routing

Traditional shore-based weather routing and some of the outdated on-board systems work as follows: routing systems try to avoid storms and therefore use speed reduction curves. [1, p.1] Information about storms is gained by surface pressure charts. The user can choose between different speed reduction curves. Such curves are defined as a function of wave height in head, beam and following seas. [1, p.1] Their result states how big the speed reduction has to be in order to avoid rough sea (i.e. storms). In order to terminate the best route, the system tries a set of candidate routes. Afterwards the route with the best fuel consumption is chosen, while the fuel consumption is calculated as follows: [1, p.2]

$$C = \frac{tons}{day} * days$$

Which leads to the conclusion that actually the voyage time is decisive for the chosen route and not the fuel consumption. Furthermore, navigation hazards and shipping lanes (i.e. traffic separation schemes) are not considered. Therefore the user has to manually update the route. After the route has been chosen and manually optimised, it is transmitted to the ship.[1, p.2]

Since this doesn't take into account the ship's reaction on weather, it can lead to needless diversions. For example the route calculation in some cases recommends to take a longer course than necessary, although the ship also could pass through the storm without any danger.

## 4.2 State of the Art Weather Routing Techniques

Modern weather routing techniques also count in other factors than only weather data (e.g. shipping lanes). But essentially they go a step ahead and consider the ship's reactions on weather conditions. [1, p.3]

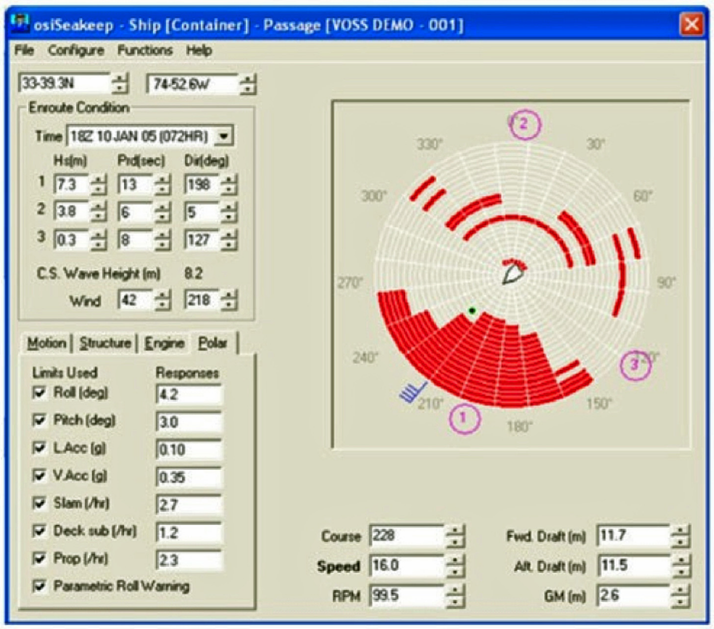


Figure 2: Polar Diagram: Safe speed and heading combinations [1, p.4]

Therefore, in a first step the ship's body plan has to be digitised. [1, p.3] Taking into account various physical properties, the program calculates the ship's reaction on waves and wind. As a first result it creates "Response Amplitude Operators". They are combined with the current weather forecast for a given time and point to predict ship's reactions. [1, p.3] Even the ship's loading conditions are essential for the calculation since the draught influences the response.[1, p.4]

The graphical visualization of the result can be seen in Figure 2. The circle represents the ship's heading. From the inner to the outer circle the speed increases. The red areas represent unsafe operation conditions.

In addition to weather, also currents may have a big influence on a ships voyage time and fuel consumption. Therefore data from ocean current models and satellite measurements is used to determine the current flow speed and direction of a current. It's obvious that a ship should go with a current and not against it in order to save time and fuel.

# 5 Algorithmic Approaches

This chapter sets its focus on the algorithmic implementation of (weather) routing algorithms. The methods presented below may have intersections with the ones mentioned in the chapter 'Weather Routing'. Most routing services take advantage of the Dijkstra Algorithm [1, p.5]. That is the reason why the Dijkstra Algorithm is not considered in depth. Instead other methods, which are more specific for vessel routing are considered. This chapter does not claim to give an overview over all methods existing. Instead a few methods are explained. If one is interested in more methods, he should have a look for the 2DDP-Method, the isopone method, or evolutionary approaches. In addition Genetic Algorithms are to mention in terms of vessel routing and the VRP. [6]

## 5.1 Isochrone Method

The recursive isochrone method is one of the first approaches on planning a route by using weather forecasts. It was introduced by R.W. James in 1957. [8, chap. 1] In the late seventies this method the first time was implemented on a computer. [8, chap. 1] Today it's considered to be depreciated. Nonetheless it's useful to know this method since evolutionary route planning approaches use it to generate an initial population. [8, chap. 1] Also some of the latest methods are based on this method.

### 5.1.1 Classic Isochrone Method

An isochrone is a set of connected points that can be reached from the origin within a given amount of time. To move forward towards the destination a second isochrone is generated, such that a perpendicular line connects the tangent of the first isochrone. [8, chap. 2.1] The points on the second isochrone can be reached from the first isochrone within the same amount of time the first isochrone can be reached from the origin.

The procedure of creating new isochrones is repeated until the desired destination is reached by an isochrone. Here you can see, why this method can be implemented recursive: The subsequent isochrone is repeatedly calculated on its predecessor.

The propeller rotating speed is assumed to be constant. [7, chap. 1] By varying propeller rotation speed, the method allows us to find the speed

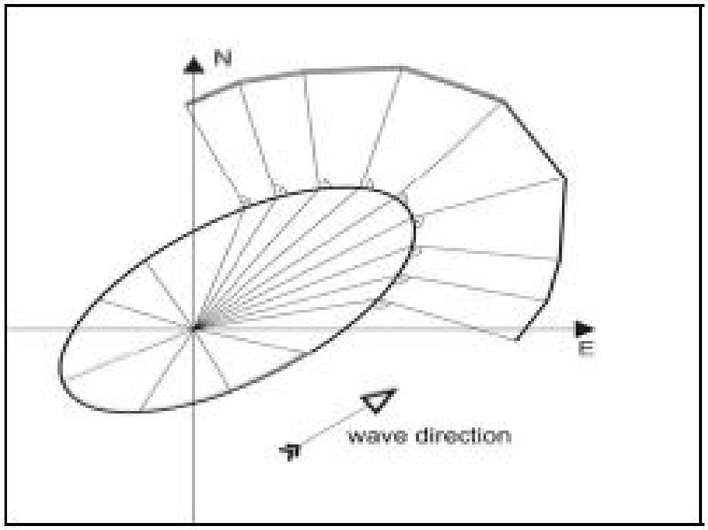


Figure 3: Visualisation of two isochrones [8, chap. 2.1]

that is needed to reach the destination within the time limits.[7, chap. 1] Since the classic isochrone methode is one of the traditional weather routing approaches, we may notice the following intersection with chapter 4.1; the minimum time route is considered to be the route with the lowest fuel consumption. [7, chap. 1]

Depending on a set of input factors (e.g. weather, ocean current) the distance between two isochrones isn't equal at any point. Obviously the ship should target the direction, where the distance between two isochrones is the largest.

If one want to implement an isochrone based algorithm he has to consider that so called "isochrone loops" may occur. They are caused by non-convexity of speed characteristic for certain weather data. [8, chap. 2.1] Also it must be ensured, that no land is crossed.

Beside that, it may happen that the user tries to find a route trough a narrow street, but the algorithm sets the isochrone points on land on the port side (left-hand side) and on land on the starboard side (right-hand side) of the waterway. Then - because of the no-land-crossing rule - the route through the narrow street is probably not found.

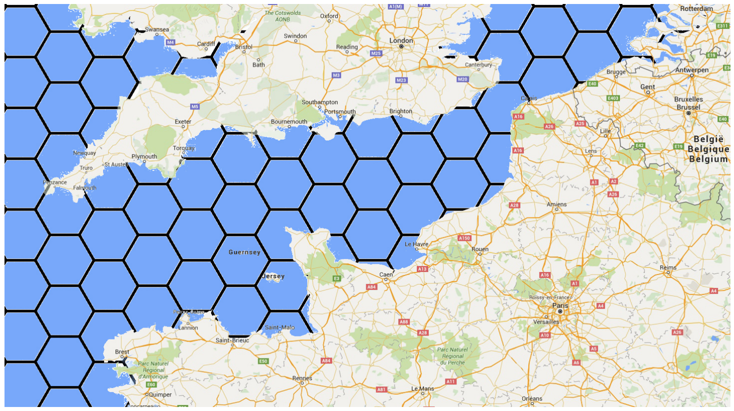


Figure 4: Visualisation of the English Channel with area partitioning

### 5.1.2 Modified Isochrone Method

The modified version of the isochrone method considers that the perpendicular to the isochrone may point into a completely wrong direction. Therefore it also takes the direction of the destination into account and propagates a course change. [8, chap 2.2] The modified isochrone method introduced by Hieki Hagiwara can also be used for minimum time/cost/fuel routing. [3]

### 5.1.3 Modified Isochrone Method with Area Partitioning

This enhanced version of the modified isochrone method was introduced by H. Hagiwara in 1989.[3] Before generating the isochrones, the search sector's area is partitioned.

In each partition only one point can be chosen. This must be the point with the maximum distance to the starting point. [8, chap. 2.3] The main advantages of this method are, that it is less prone to the non-convexity-error and routes trough narrow streets can be found easier, since even a small waterway must be part of a partition. [8, chap. 2.3]

## 5.2 3DMI Method

The 3-Dimensional Modified Isochrone Method (3DMI) is also called 3-Dimensional Dynamic Programming (3DDP) Method. It is an extension of the 2DDP method which is similar to the modified isochrone method.[7, chap. 1] The

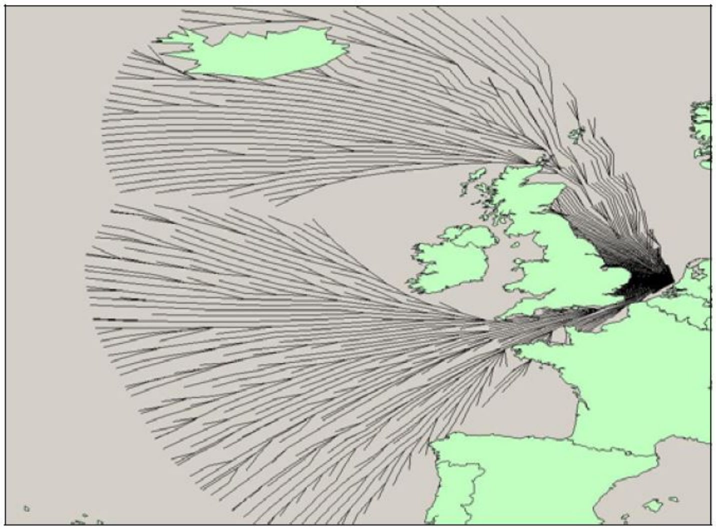

Figure 5: Typical representation of the modified isochrone method with area partitioning [8, chap. 2.3]

method breaks the problem of calculating a route from A to B down into many sub-problems. [7, chap. 3.1]

**Theoretical Problem Statement**

First, the problem is described in a formal way as done in [7, chap. 2].
Control Vector:

$$\vec{U} = (u, \psi)$$

Position Vector:

$$\vec{X} = X(\phi, \theta)$$

Weather Condition:

$$\vec{E} = E(\vec{X}, t)$$

Ship position $\vec{X}$ at time t:

$$\vec{X} = f(\vec{X'}, \vec{U'}, \vec{E'}, \vec{C'})$$

where the input vectors correspond to time t' (t-t' = $\Delta$t). This function can be explained as follows: position $\vec{X}$ is reached from position $\vec{X'}$ under certain weather condition, a certain speed and course and while complying with the constraints within $\Delta$t.

| | |
|---|---|
| u | ship speed over ground |
| $\psi$ | shipping course |
| $\phi$ | longitude |
| $\theta$ | latitude |
| t | time |
| $\vec{C}$ | constraint vector |

Table 1: List of symbols used in the problem statement

**How does this method work?**

The basic steps are the following: [7]

- The great circle line is set as an initial solution.
- The search area is divided into stages.
- Each state consists of many states.
- A state is a measurable condition (e.g. time and position of the ship).
- The forward calculation is done.
- Afterwards the backward calculation is done.

Figure 6 shows an initial solution with its states and stages.

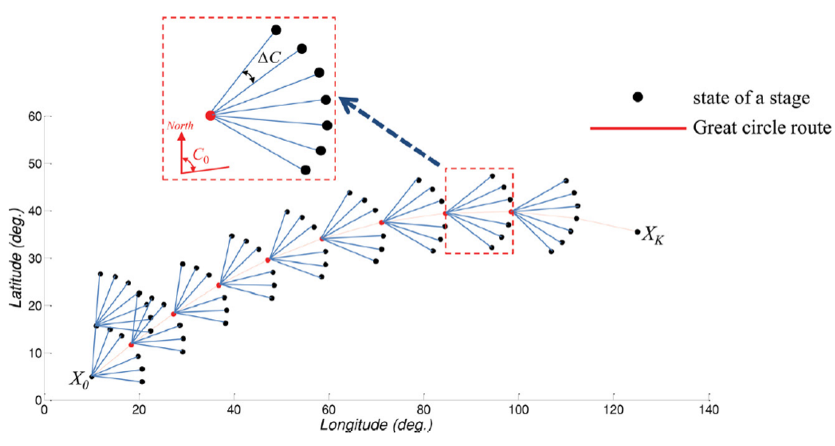


Figure 6: Initial Solution for 3DMI-Method [9, fig. 3]

In figure 7, the forward calculation is visualised as a Nassi-Shneiderman diagram. A textual representation can be found in [7, chap. 3.4].

Basically the calculation can be summarised as follows: For each state of each stage the fuel consumption ($\Delta f$) and voyage time ($\Delta t$) to all states on the next stage are calculated. This is done for various different speeds. If the current calculation violates restrictions, this particular calculation step is skipped or fuel consumption is set to infinite. Else the results are saved for backward calculation.

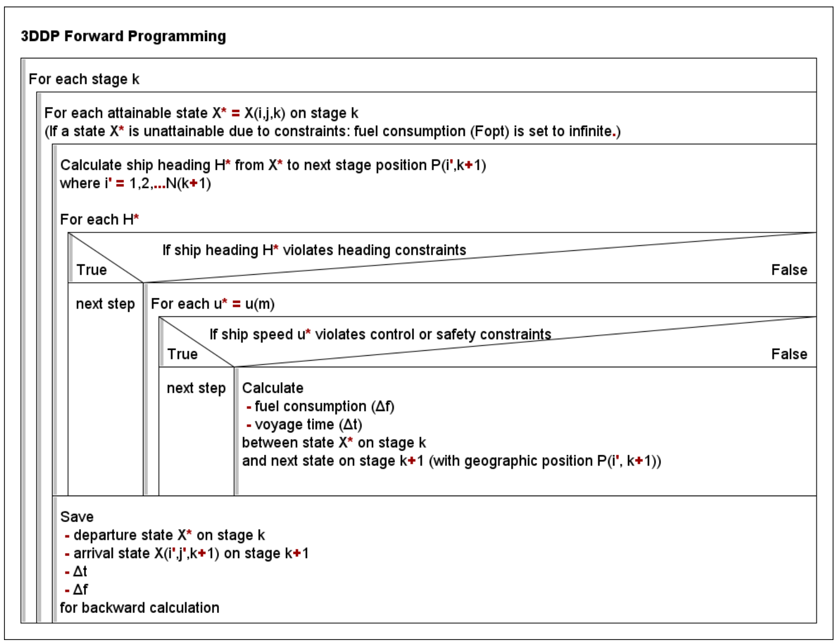


Figure 7: Nassi-Shneiderman diagram of 3DMI forward programming

The forward calculation is finished, if the finale state on the last stage is reached. Afterwards the backward calculation is made. All possible state combinations are created and the $\Delta$-values ($\Delta f$ and $\Delta t$) are summed up in each possible combination. There are $states^{stages}$ combinations. Figure 8 shows the visualisation of the result like Jeppesen VVOS (Vessel and Voyage Optimization Solution) presents it to the user. Depending on his requirements, the user can choose a fast route with high fuel consumption, a route that takes more time but saves fuel or one that offers a moderate fuel consumption and acceptable voyage time.

| | |
|---|---|
| k | stage |
| N(k) | total number of states on stage k |
| j | time interval between states |
| x(i,j,k) | state i on stage k at time j |
| P(i,k) | state position |
| u(m) | ship speed, u(m) = 5 + 0.1*(m-1) where m = 1,2,3..M |
| F(X(i,j,k)) | minimum fuel consumption from initial state to state X(i,j,k) |

Table 2: List of symbols used in figure 7

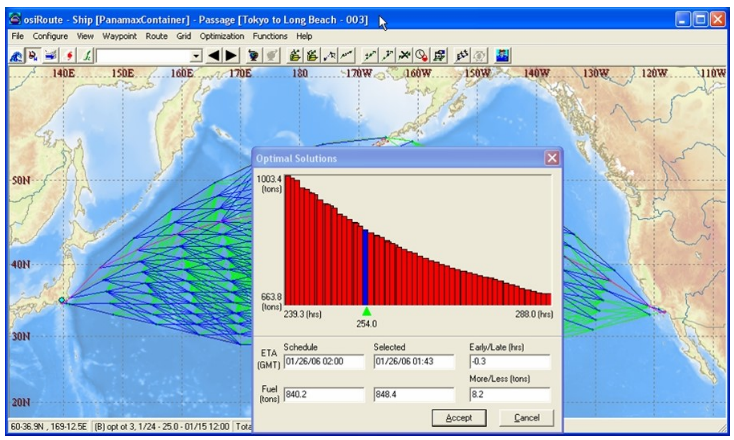


Figure 8: Possible routes after backward calculation [4]

**Case Study**

Since fuel cost constitute the most significant cost factor for ship owners, they are interested in reducing fuel consumption.[5, p. 22] Depending on the ship, approximately 6,000 metric tons of bunker fuel are burned on a voyage from Europe to Asia. Compared to an older method (2DDP) the 3DDP method enables the ship owner to save up to 5 percent of bunker fuel. [7, chap. 4] Rated with average prices, the 5 percent reduction in fuel consumption leads to a saving of approximately 60,000$.

## 5.3 Graph-based Algorithm (Dijkstra)

Many weather routing software solutions rely on the Dijkstra Algorithm. [1, p. 5] For utilization in the field of maritime routing I would recommend to replace the edge weights by a weighting function. Beside the economic optimization (i.e. minimizing cost and/or voyage time), the function should ensure that safety is granted. For example if land is crossed or the water depth is not sufficient, the functions result must be significantly higher than normally. An other approach could be to use a function that returns two values. The weight and a boolean that states if the according edge must be excluded from further calculations.

Since the Dijkstra Algorithm is no specific approach for maritime applications and commonly used, it is not considered in depth. Various information and implementation examples can be found on the internet or in literature.

# 6 Software Presentation

As an example for a weather routing software, we will have a closer look at OpenCPN (http://opencpn.org/ocpn/).

OpenCPN is an open source software under GPLv2 license. It can be used as chart plotter, as well as navigation software. The software can be extended by using plug-ins. The weather routing functionality for example is realised as a plug-in.

## 6.1 OpenCPN Chart Plotter

As a groundwork for navigation, accurate maps are needed. The chart plotter visualises the map data. There is a built in world map which provides a low resolution but already comes with tides and currents information for certain areas. To gain a better resolution additional maps can be downloaded. Most countries offer free map data of their inland waterways and shore zones.

A list of free sea vector charts can be found on the internet.(`https://openseachart.org/doku.php/enc`) OpenCPN itself offers a list of further map sources. (`http://opencpn.org/ocpn/chart_sources`)

However, the most comfortable way to add additional map data to OpenCPN is to use the Plugin 'Chart Downloader'.

## 6.2 Weather Routing in OpenCPN

As mentioned, first the weather routing plug-in must be installed. Afterwards current weather data and forecasts must be added. OpenCPN uses GRIB

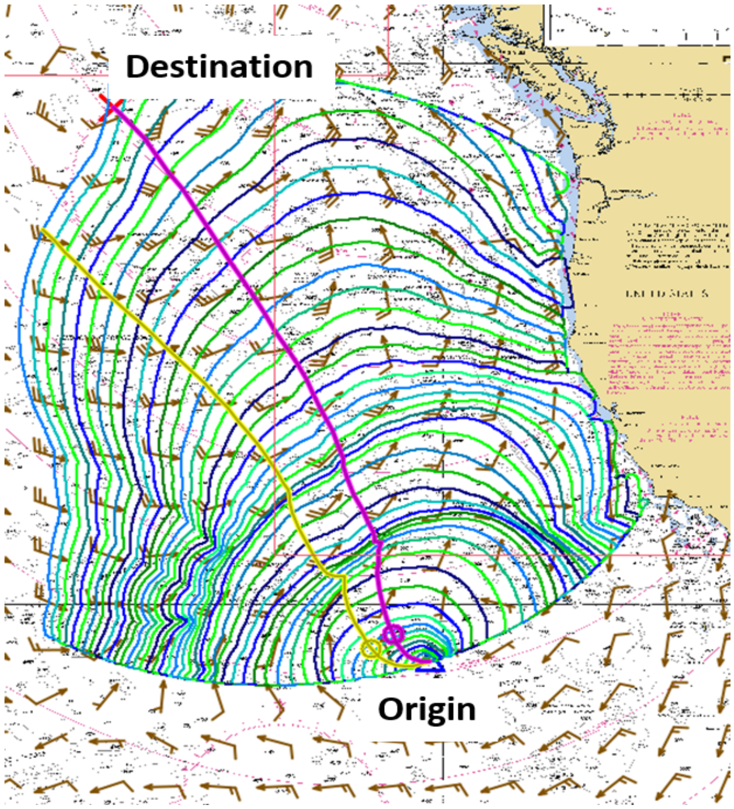


Figure 9: OpenCPN route visualisation

files as data input for weather information. Wave and wind data usually is provided in separate files. Free GRIB files can be found on the internet. (`http://www.globalmarinenet.com/free-grib-file-downloads/`)

After a sufficient map is loaded, the weather routing plug-in is installed and current weather information are present, the route calculation can be initiated by defining two new 'Weather Route Positions' on the map. In order to define the ship's characteristics one can create and manipulate the 'boat file' which holds information about the ship's properties. Afterwards the calculation can be started.

Obviously the weather routing plug-in uses a version of the modified isochrone method, since calculation is directed towards the destination. No, or depending on the weather data, less calculations in the opposite direction are done.

# 7 Conclusion

Shipping is a very old industry and that's why calculating a route for a vessel from A to B must be almost the same age. As we have seen, there are various approaches and enhancements of these approaches. Scientists made huge efforts in creating reliable algorithms and the market offers powerful solutions to the ship owners which support them in planning a route for a certain vessel.

Nonetheless there is potential to improve existing software. Especially because of the huge amount of input factors to be considered, algorithms of the future should learn to make individual decisions for each ship. Furthermore the change of input factors by time should be considered. For example it could be helpful to predict fuel prices on historical data to determine the optimum port to refuel.

# 8 Glossary

**3DDP** 3-Dimensional Dynamic Programming. 8

**3DMI** 3-Dimensional Modified Isochrone Method. 8

**isochrone** Set of connected points, that can be reached within a given amount of time.. 5

**Response Amplitude Operator** Interim result of simulation of the ship's reaction to certain weather conditions. Combined with weather forecast data, the actual response of the ship can be gained.. 4

**SECA** Sulphur Emission Control Area - Areas with strict emission limits for ships. In order to comply with these regulations, shipowner have to use sulphur reduced fuels which are more expensive than normally used fuels.. 2

**SPP** shortest path problem. 2

**Traffic Separation Schemes** In busy waterways - usually around capes - Traffic Separation Schemes are established in order to manage a high traffic density.. 2

**TSP** traveling salesman problem. 1

**VRP** vehicle routing problem. 1, 5

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