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Vessel Routing as an Application of the Shortest Path Problem

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0. Content

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How many containers are being lost aboard every year?

Image source: www.maritimenz.govt.nz

Importance of Vessel Routing

- Up to thousands of containers are lost overboard on sea every year.
- On-time performance:
  - Low: < 50%
  - High: 85 %
- Security Reasons
- Cost

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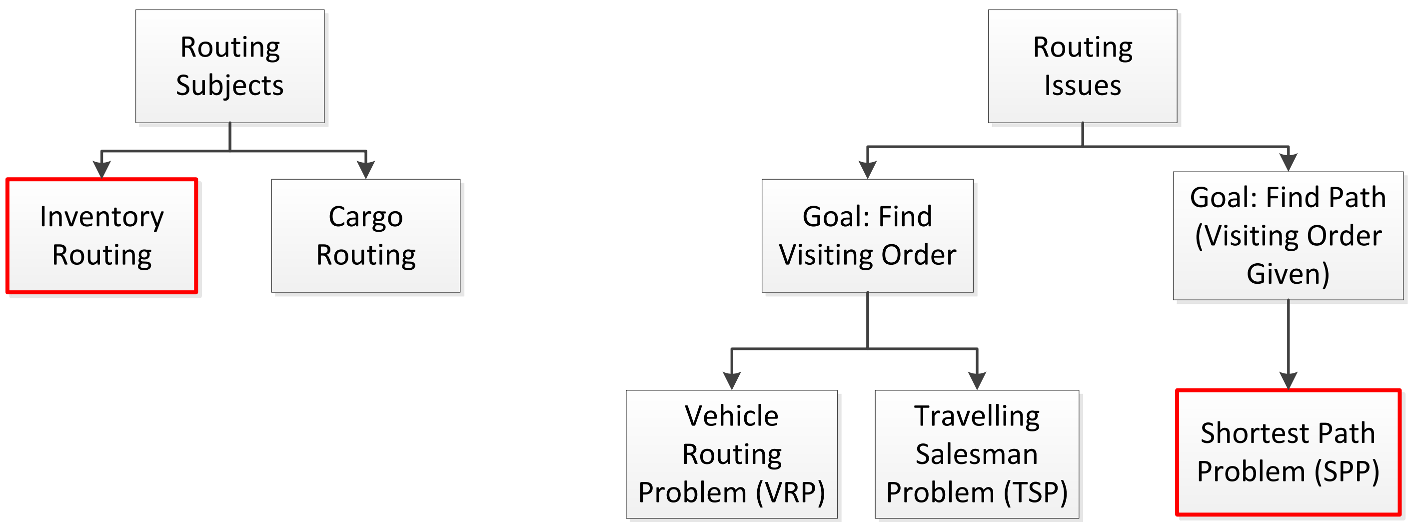
Classification



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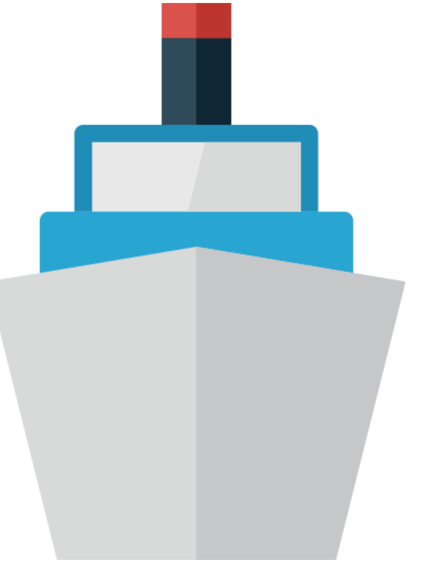
Objectives

- Cost
- Distance
- Time

- Safety
- Security



Restrictions

- Nautical Restrictions (e.g. draught, height, breadth, length)
- Weather (e.g. waves, currents, wind)
- Legal Restrictions (e.g. SECA, Traffic Separation Schemes)
- Security Restrictions (e.g. piracy areas or battle zones)
- Cost (e.g. crew wages, charter cost, fuel costs, toll)

Traditional Weather Routing

- shore-based or onboard systems
- principle: storm avoidance
- data input: pressure charts
- several candidate routes are tried
- assumes the fastest route to be the cheapest
- the physical reaction of the ship to waves and wind is not taken into account

3. Weather Routing

- Since it only focuses on weather: no consideration of other restrictions.
- Route needs to be manually updated in order to consider navigation hazards and shipping lanes.
- no fuel saving optimizations
- probably needless ship diversions

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Modern Weather Routing

- also takes into account other factors than weather (shipping lanes, navigation hazards…)
- considers ship’s reaction to waves, wind and currents
- needs a digitized body plan of the ship

3. Weather Routing

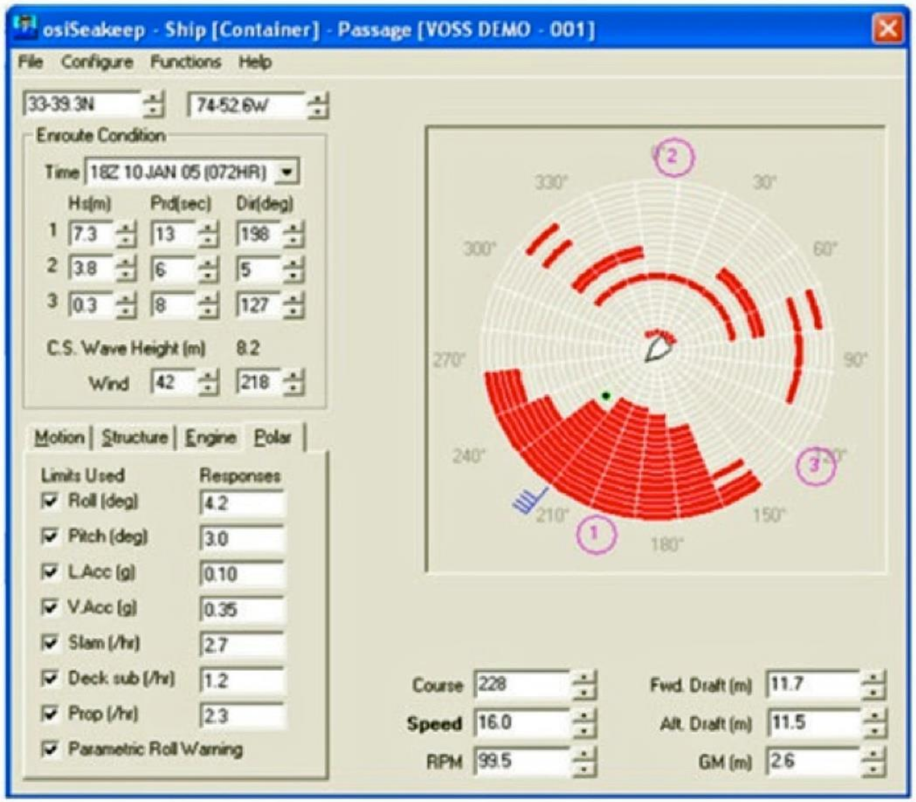

Image source: jeppesen.com

Examples of Methods

- Calculus of Variations
- Dijkstra Algorithm
- Isochrone Method
- Modified Isochrone Method
- Isopone Method
- Three-Dimensional Dynamic Programming
- and many others…

4. Algorithmic Approaches

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To use shortest-path algorithms in order to optimize cost or fuel consumption instead of distance:

Replace distance by overall cost or fuel consumption of the according distance

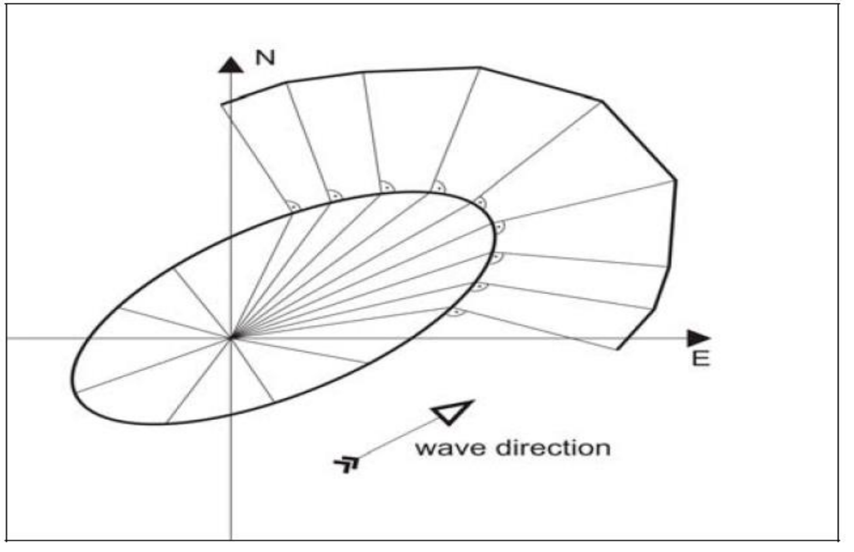
Classic Isochrone Method

- introduced in 1957 by R.W. James
- first computer implementation in the late 1970s
- Although it is deprecated, the method is useful because it generates initial solutions for other approaches. In addition several improvements for this method are provided.

Characteristics

- Isochrone: A set of connected points that can be reached from the origin within a given amount of time.
- recursive algorithm, calculates repeatedly isochrones
- prone to isochrone loops due to non-convexity of isochrones

1. create first isochrone: $isochrone_0$
2. create $isochrone_{i+1}$ in that way, that a perpendicular line connects the tangent of $isochrone_i$
3. repeat step 2 until the destination can be reached within an isochrone



Modified Isochrone Method

- Takes into account that the perpendicular to the preceding isochrone is not necessarily the best option.
- therefore propagates a course change
- solves the isochrones loop problem
- widely used since more complex methods are difficult to understand by the operators on the ship
- can cause problems when crossing a narrow street (e.g. English Channel or even smaller)

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Modified Isochrone Method with Area Partitioning

- the search sector is partitioned
- in each area the point with the maximum distance to the origin is selected

4. Algorithmic Approaches
4.2. Modified Isochrone Method

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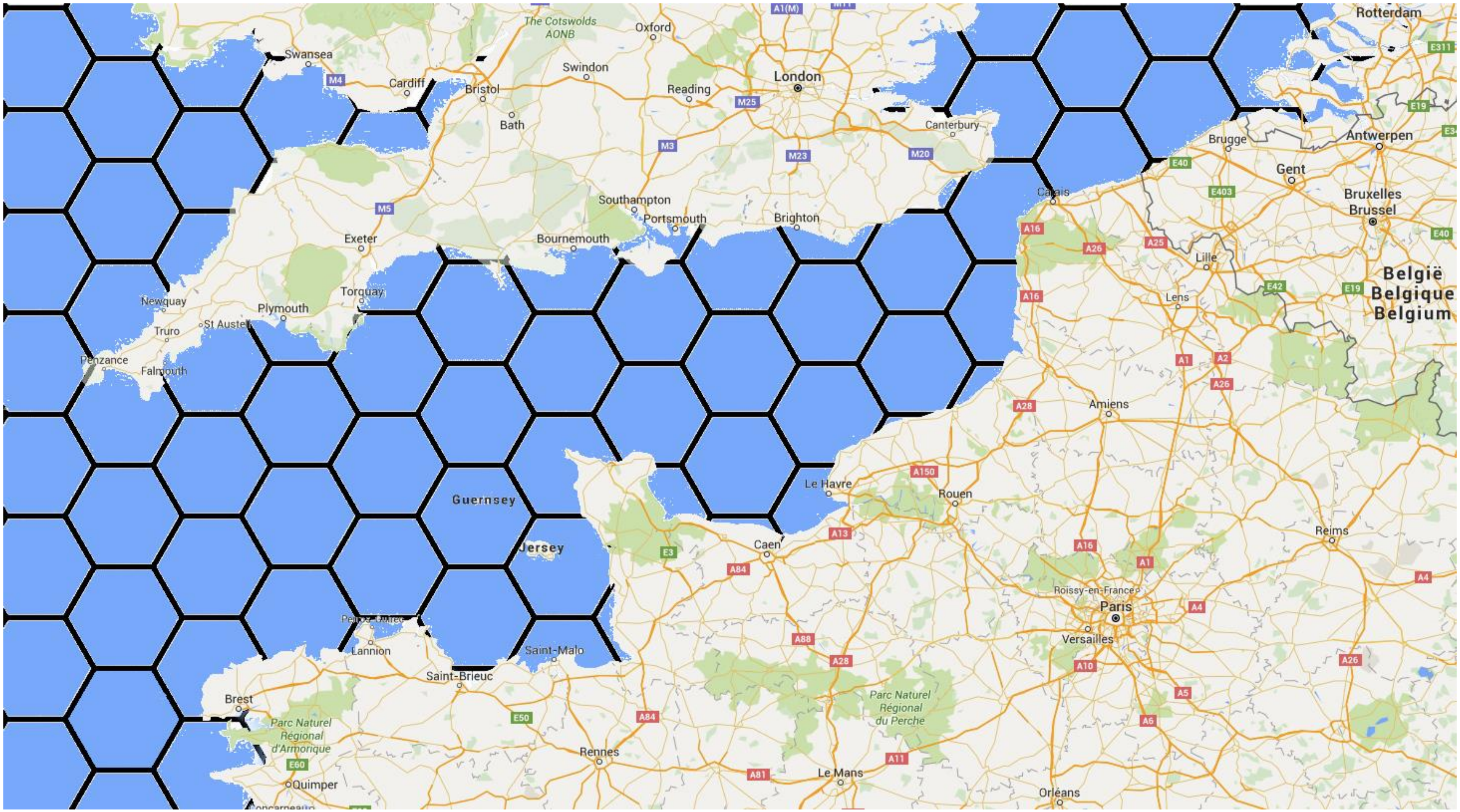

Implementation

1. start and destination may not lay on landmass
2. creation of a new isochrone candidate point: ensure that a line to its predecessor does not cross landmass

   → if it does: a new point must be found
3. when selecting the last isochrone point that represents the destination: check that no land is crossed

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How to Check if Land is Crossed?

- There is no sufficiently fast and robust algorithm to check if a line between two points intersects a polygon.

Solution

1. create a bitmap for the entire map
2. a bitmap cell is set to ‘true’ if it represents land, to ‘false’ if not
3. store the bitmap for future use
4. for each cell that represents the line between the two points: check if there is land

4. Algorithmic Approaches
4.3. Implementation of the Isochrone Method

3DMI Method

- 3DDP: 3-Dimensional Dynamic Programming
- 3DMI: 3-Dimensional Modified Isochrone Method
- allows to take into account navigation boundaries
- breaks the problem down into sub-problems

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Characteristics

- search area is divided into in stages
- each stage consists of many states
- a state is a measurable condition of the ship operation (e.g. time and location)
- forward and backward calculation

Theoretical Problem Statement

- control vector: $U^{\rightarrow} = U(u, \psi)$
  - u = speed
  - ψ = shipping course (heading)
- position vector: $X^{\rightarrow} = X(\varphi, \theta)$
  - φ = longitude
  - θ = latitude
- time: t

- weather: $E(X^{\rightarrow}, t)$
- constraints: $C^{\rightarrow}$
  - geopgraphic, control, safety constriants

<u>Future Position</u>

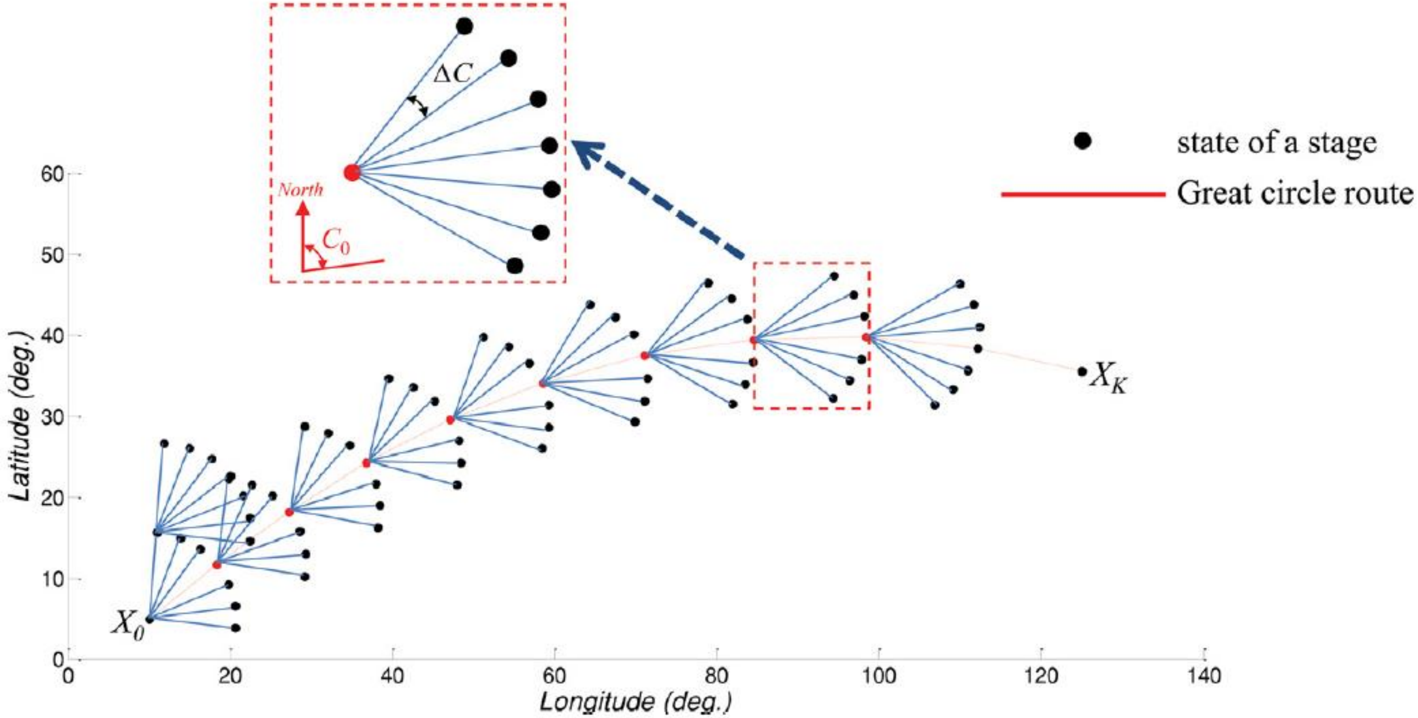
- ships position $X^{\rightarrow}$ at time t:

$$X^{\rightarrow} = f(X^{\rightarrow\prime}, U^{\rightarrow\prime}, E^{\rightarrow\prime}, C^{\rightarrow\prime})$$

- where $X^{\rightarrow\prime}, U^{\rightarrow\prime}, E^{\rightarrow\prime}, C^{\rightarrow\prime}$ corresponded to t'
- and $t - t' = \Delta t$

Procedure

1. Create Initial Solution:



2. Forward Calculation

Notations

- k: stage; K: total number of stages
- N(k): total number of states on stage k
- j: time interval between states; J: total number
- X (i,j,k): state i on stage k at time j
- P (i,k): state position
- u(m): ship speed over ground
- F_{opt}(X(i,j,k)) = minimum fuel consumption from initial state to state X(i,j,k)

4. Algorithmic Approaches
4.4. 3DMI/3DDP

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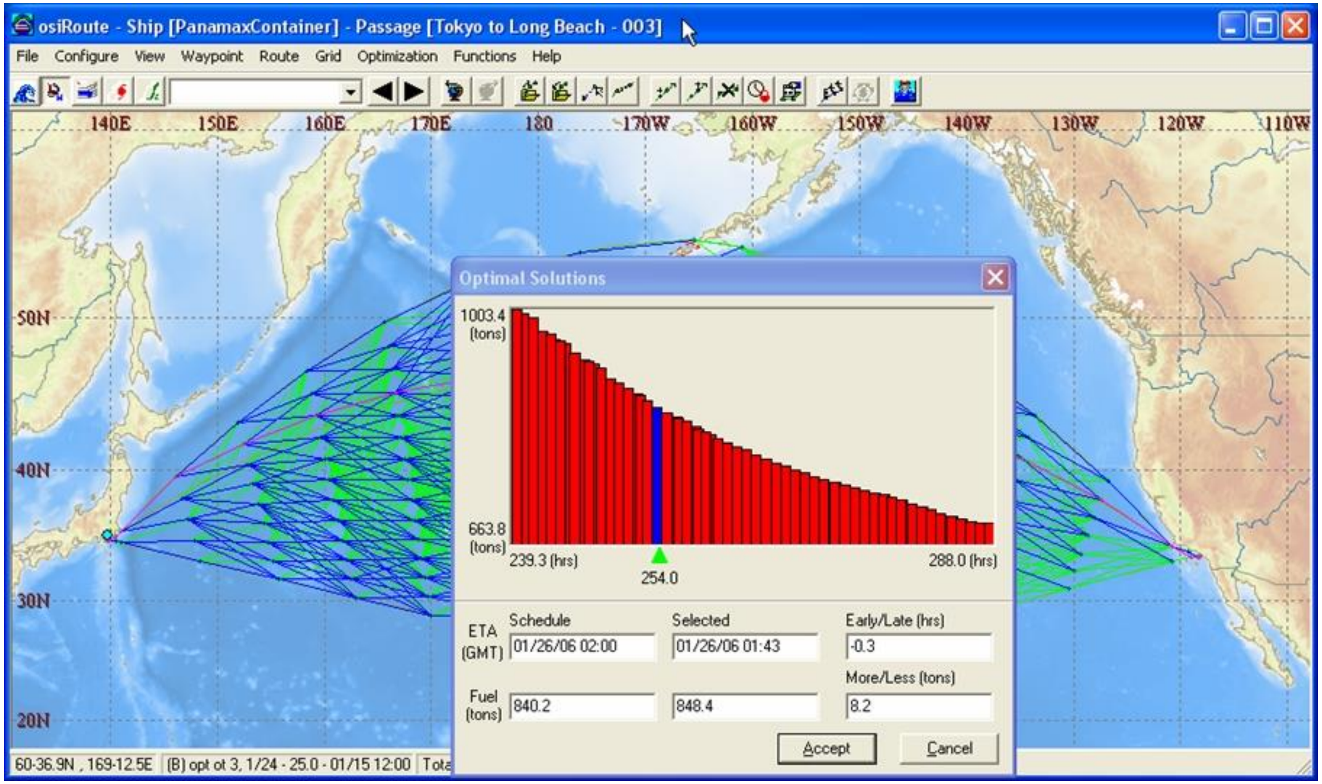

Image source: ww1.jeppesen.com/

3. Backward Calculation once the finale state on stage K has been obtained:
   - We now have a grid with weighted Δt and Δf values.
   - Do a backward calculation to identify the optimized fuel consumption route with the specified arrival time.
   - Therefore create all possible state combinations

Case Study

- Compared to an older method (2DDP) the 3DDP method saves up to 5% fuel.
- Fuel is the most significant cost factor for ship owners. (approx. 45% of operating cost)
- Approximately 6000 metric tons of fuel are burned for a voyage from Europe to Asia.
- Rated with current prices a 5% reduction of fuel consumption saves 60.000$ for a Europe-Asia one-way voyage

OpenCPN Demonstration

A Chartplotter and GPS Navigation Software.

http://opencpn.org/ocpn/

6. Sources

- Development of a 3D Dynamic Programming Method for Weather Routing (S. Wei & P. Zhou)
- Voyage Optimization Supersedes Weather Routing (Henry Chen/Jeppesen)
- Adopted Isochrones Method Improving Ship Safety in Weather Routing with Evolutionary Approach (Szlapczynska Joana, Smierzchalski Roman)
- The optimization of ship weather-routing algorithm based on the compsite influence of multy dynamic elements (Yu-Hsien Lin, Ming-Chung Fang, Ronald W. Yeung)

Image source: de.toonpool.com