Ship routing and scheduling: Theory and practice

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MARITIME TRANSPORT OPTIMIZATION:
AN OCEAN OF OPPORTUNITIES

Shipping company planners face complex problems every day.
Now, thanks to O.R., help is on the way.

Today’s globalization would be impossible without modern, cost-effective merchant ships crossing the seas. World trade was 5-6 times as high at the end of the 20th century, as it was 50 years previously. A shipping industry that has steadily lowered its costs has been a prerequisite of this development, and there are no signs that the world economy will only grow but increasingly rely on sea transport in the future.

BY MARIKLE CHRISTIANSEN, KJETIL FAGENHOLT, Geir Hasle, Atle Minsaas and Bjørn Nygren

NTNU
Outline

• Ship routing and scheduling problems
  – Including some discussion on problem complexity
• Traditional planning methods used by shipping companies
• Heuristic solution methods – an introduction
• Developing TurboRouter – an optimization-based DSS for ship routing and scheduling
• Demonstration of TurboRouter
• Experience from implementing TurboRouter
• Complicating aspects
• Summary and concluding remarks
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Importance of proper planning

- Ships involve major investments and high operating costs
- Reducing costs through good planning is important
- Increasing revenue by carrying more spot cargoes by utilizing the fleet better contributes even more!
Tramp ship routing and scheduling

- Perspective of the planner(s) in a tramp shipping company
- What is the planning problem he/she daily struggles to solve?
- What information is needed?
Ships

- The planners are responsible for a given fleet (fleet segment)
- Each ship in the fleet has a set of attributes:
  - Capacity (weight/volume)
  - Fuel consumption pattern
  - Service speed (laden/ballast)
  - Loading/unloading rates
  - Etc...
Contract cargoes

• Engaged in long-term contracts with shippers
• From each contracts, the shipper will give notices on actual cargoes (liftings) some time in advance
• Each cargo has the following attributes:
  – Loading and unloading port
  – Quantity
  – Time window for loading or unloading (laycan)
  – Product
  – Income
  – Etc.
• All contract cargoes must be serviced
Spot cargoes

- The planner also receives requests for optional spot cargoes from brokers.
- Once such a request is received, the planner must decide whether to negotiate for the spot cargo.
- Until a deal is closed, a spot cargo can be treated as optional.
- When a deal for the spot cargo is closed, it must be treated as a contract cargo.
  - It must be serviced.
Planning objective

- Short-term routing and scheduling problem
  - Planning horizon depends on operation
- **Objective:** Develop a vessel fleet schedule that maximizes profit (gross margin)
  - Net income (gross margin)
  - Net daily (gross margin per day the ships are in use)
- Income components:
  - Income from contract cargoes
  - Income from optional spot cargoes
- Main cost components (variable):
  - Fuel costs
  - Port fees (depend on ship size)
  - Canal fees (depend on ship size)
Constraints

- Service all contract cargoes
- Ship capacity
- Time windows
- Compatibility
  - Ship – port/canal (e.g. draft restrictions)
  - Ship – product
Routing and scheduling

- Assigning cargoes to available ships
- Deciding optimal visiting routes/sequences for each ship

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<td>5</td>
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</table>
Single ship routing

- A Travelling Salesman Problem (TSP) with side constraints
- Assume no side constraints
- For a problem with $n$ nodes (post visits), what is the number of routes visiting all nodes?
  - $(n-1)!$
- TSP is a complex combinatorial problem
Assigning of cargoes to ships

- Assigning cargoes to available ships
- Also a complex combinatorial problem
  - 3 ships and 5 cargoes $\Rightarrow$ 243 alternatives
  - 10 ships and 20 cargoes $\Rightarrow$ 100,000,000,000,000,000,000
  - $m$ ships and $n$ cargoes $m^n$
Routing and scheduling

• Assigning cargoes to available ships
• Deciding optimal visiting routes/sequences for each ship
• Assignment and routing must be solved simultaneously
• Constraints must be satisfied:
  – Capacity
  – Time windows
  – Compatibility
  – Etc...
• Pickup and Delivery Problem with Time Windows
Planning process

- Mix of mandatory contract cargoes and optional spot cargoes
- Planner has to negotiate spot cargoes and schedule the fleet
  - Continuous and interwoven process
- Rolling horizon principle
- Core business for many tramp shipping companies!
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Traditional planning methods

- Using a voyage estimation software
  - Calculates only one voyage for one vessel simultaneously
- Few optimization-based DSSs in use
- Building complete schedules is often done manually based on experience
- Graphical problem representation
- Spreadsheet for visualization

- Improvement potential is significant!
## Example: Manual planning worksheet

### UK/CONT
- Milford Haven – New York
  - MTBE: 40,000 ton
  - Dates: 3/11-07 – 9/11-07
- Antwerp – Boston
  - MTBE: 37,000 ton
  - Date: 5/11-07 – 10/11-07

### MEDIT
- Cartagena (SPA) – Houston
  - MTBE: 28,000 ton
  - Dates: 15/11-07 – 19/11-07
- Algeciras – Charleston
  - Methanol: 16,000 ton
  - Dates: 15/11-07 – 20/11-07

### CARIB
- Point Lisas – Houston
  - Methanol: 17,000 ton
  - Dates: 4/11-07 – 10/11-07
- Jose – New Orleans
  - Methanol: 30,000 ton
  - Dates: 4/11-07 – 10/11-07
- Jose – New York
  - Methanol: 18,000 ton
  - Dates: 10/11-07 – 15/11-07

### US/GULF
- Houston – New York
  - MTBE: 18,000 ton
  - Date: 6/11-07 – 11/11-07

### Vessels
- **Cecilia**
  - Antwerp 2/11-07
- **Catharina**
  - Antwerp 7/11-07
- **Suzanna**
  - Jose 15/10-07
- **Alberta**
  - Boston 4/11-07
- **Maria**
  - Charleston 23/10-07
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Heuristic methods for ship scheduling

- A heuristic is a set of rule-of-thumbs
- Most often to be performed on a computer
- Can generally not guarantee optimal solutions, but will often produce good solutions quickly
An example: The knapsack problem

• Suppose you are planning a mountain hiking-trip and would like to maximise the utility of the content to carry in the knapsack
• You cannot carry more than 11 kilograms
• You have four items you would like to carry:

<table>
<thead>
<tr>
<th>Item</th>
<th>Weight</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermos bottle</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Primus</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Sausages</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Mountain tent</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>
Example (cont.): Greedy heuristic

• Sort the items according to utility per kilogram
  • $8/1 > 10/3 > 15/5 > 16/6$
  • Thermos bottle > Primus > Sausages > Tent

• Start filling up the backsack:
  – Start with Thermos bottle => remaining capacity of 10
  – Primus => remaining capacity of 7
  – Sausages => remaining capacity of 2, which we cannot use

• Total utility of solution: 33

• Optimal solution: 34 (including thermos bottle, primus and tent)
Why use heuristics?

- Exact methods may not be able to solve these complex routing and scheduling problems
- Solutions are often needed quickly (especially during the spot cargo negotiation process)
- Often better to find a good solution to the problem, rather than an optimal solution to the model of the problem
A local search heuristic for ship routing and scheduling*


Generating initial solution - Insertion heuristic

1. Select one cargo at a time
2. Evaluate all insertions into all ships’ routes and choose the best feasible insertion/ship according to some criteria
3. If all cargoes have not been evaluated, go to 1

- Myopic algorithm – will most often produce poor solutions
Improving solution - local search

• Define a **neighborhood** based on specific moves (**local search operators**)
Local search operator: 2-interchange

Ship \( v \)

Ship \( u \)
Improving solution - local search

- Define a *neighborhood* based on specific moves (*local search operators*)
- Explore all neighborhood solutions in a systematic way until no further improvement can be found
- What can we say about the quality of such a solution?

- *Local optimum*
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Initial design of TurboRouter

- MARINTEK started a research project in 1996
- Funded by the Norwegian Research Council and MARINTEK
- Established a project group together with a few shipping companies as strategic partners
  - Jebsen Management, operating appr. 10 self-unloaders for dry bulk shipping
  - Iver Ships, operating appr. 25 chemical tankers
- Aim in beginning: Develop optimization software for fleet scheduling
- However, most shipping companies sceptical to such systems
  - Conservative industry?
  - Planners afraid of becoming redundant?
  - Impossible to handle all practical constraints
- Change of focus from optimization to decision support
Example of constraint that is hard to model

- Compatibility port - ship due to draft restrictions in port
- Suppose a ship can enter the port:
  - if not fully loaded
  - at high tide
- This constraint will be influenced by the
  - vessel’s draft
    - which again is influenced by the cargo quantity onboard (and also if it is summer/winter)
  - port’s draft restriction
    - which again is influenced by tidal factors

- Even if it was possible to model such constraints, it would not be desirable, as the users would not trust it
- Only an experienced planner can/should evaluate this constraint from situation to situation
Initial design of TurboRouter

- Information system for vessels, ports, distances, etc...
- Much focus on graphical user interface facilitating user interaction
- Electronic sea charts
- Satellite position reports gave an instant overview of vessel positions
- We developed an algorithm for calculating port-port and ship-port distances*
  - dynamic distance tables
  - updated ETAs from vessels

Initial design of TurboRouter (2)

- Based on the distance calculation algorithm, Jebsen Management and we came up with the idea of the Schedule Calculator.
- Used for manual planning of vessel schedules.
- Used by Jebsen with great success.
- Still only considering one vessel simultaneously.

Arrival time and bunker consumption is calculated automatically.

Click a port, and the system calculates the distance and sailing time to the next selected port.
Vessel fleet schedule optimisation

- The success of the simple manual scheduling tools gave confidence from the shipping companies which again resulted in new projects
- In 2000, we started developing a function for vessel fleet scheduling optimization together with Jebsen Management and Iver Ships
- Much emphasis on user interface and interaction
- Less focus on solution algorithm
  - Needed quick ‘visual results’
  - Initially it was only a simple insertion method
  - (Now there are much more sophisticated “state-of-the-art” methods)
- Some complex constraints cannot (or is not desirable to) be modelled
- Objectives may be multiple
- Therefore, it should be possible to easily construct a fleet schedule manually, as well as overrule suggestions by the system
Alternative solutions for a real small-sized problem

- Solution 1: Manual solution provided by shipping company
- Solution 2: TurboRouter solution
- Solution 3: Manual adjustment of TurboRouter solution
- Solution 4: Manual solution

Which solution is best?
- Solution 1 is best with respect to Capacity utilisation
- Solution 2 is best with respect to Net Income and # cargoes
- Solution 3 is best with respect to Net Daily
- Solution 4 is best with respect to total quantity shipped and # cargoes

=> Important with user decisions!
Short demonstration of TurboRouter*


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Impact on scheduling - results

• Shuttle tank operation:
  – Benchmark again manual solutions for the first weeks
  – Two additional spot cargoes lifted
  – 1 - 2 mill. USD on bottom line!

• Product tanker operation
  – Excellent decision support in negotiation process
  – 1 - 2 % increased profit in a poor market
  – Assume better results in a better market

• Other shipping companies
  – Used the DSS also for evaluating strategic issues
  – Contract evaluation
  – Fleet size

• Etc…
Summary on implementation aspects

• The ‘human factor’ is extremely important
• User interface and interaction is even more important than good optimization algorithms
  – at least in the initial process of getting approval from the users
• Success criteria:
  – Knowing the shipping industry
  – Need a ”Champion” in the shipping company
  – Involvement from users in the design and implementation
• Still, only few shipping companies use optimization-based DSSs
• Maritime logistics focused research area in Norway
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Robust planning in short sea shipping*

- **Example:** port open 8 - 16 weekdays, effective time in port 12 hours, time window (laycan): Wednesday - Monday

- **Risky arrival:** planned finish in port just before closing on Friday afternoon

Flexible cargo quantities*

- Two types of contracts:
  - MOLOO: More Or Less (ship)Owners Option
  - MOLCO: More Or Less Carriers Options
- Cargo quantity specified within an interval \([q_{min}, q_{max}]\)
- Typical commodities:
  - Dry bulk
  - Chemicals and oil products
- Utilizing flexibility in quantity can reduce sailing costs and increase revenue by carrying more spot cargoes


* Brønmo and Nygreen (2009) Column generation approaches to ship scheduling with flexible cargo sizes. Accepted in *European Journal of Operational Research.*

Example: Routing one ship

<table>
<thead>
<tr>
<th>Cargo Information</th>
<th>Load</th>
<th>Unload</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo 1</td>
<td>R</td>
<td>A</td>
<td>0.6 ship</td>
</tr>
<tr>
<td>Cargo 2</td>
<td>L</td>
<td>M</td>
<td>Full ship</td>
</tr>
<tr>
<td>Cargo 3</td>
<td>K</td>
<td>L</td>
<td>0.5 ship</td>
</tr>
</tbody>
</table>

Physical route for a ship:

Load onboard the ship at departure:
- Cargo 1
- Cargo 3
- Cargo 2
Example cont.: Introducing cargo flexibility

<table>
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<td>R</td>
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</tr>
<tr>
<td>Cargo 2</td>
<td>L</td>
<td>M</td>
<td>Full ship</td>
</tr>
<tr>
<td>Cargo 3</td>
<td>K</td>
<td>L</td>
<td>0.5 ship</td>
</tr>
</tbody>
</table>

New!
Flexible sizes
0.5 - 0.7 ship
0.4 - 0.6 ship

• Several cargoes can be carried simultaneously

Physical route

Load onboard the ship at departure

- Cargo 1
- Cargo 1 and Cargo 3
- Cargo 3
- Cargo 2
Effect of utilizing cargo flexibility: An example

![Graph showing the effect of utilizing cargo flexibility. The graph plots the increase in objective value (%) against the quantity interval (+/- %). The line represents Case 4.]
Stowage considerations*

• Routing decisions may often depend on stowage feasibility
• Ships usually have a defined number of tanks in which cargoes can placed
• Some aspects to be considered:
  – Stability and strength (in several dimensions)
  – Cannot mix different products in the same tank
  – Tank sloshing
  – Hazardous materials cannot be located close to each other
  – History of tank usage (cleaning of tank may be required before use)


Speed optimization*

- Fuel consumption costs per unit of time can for most practical speeds be estimated as a cubic function of speed
  - Or a quadratic function of speed per nautical mile, for example:
    \[ f(v) = 0.0036v^2 - 0.1015v + 0.8848 \]
- A defined ‘service speed’ is usually used in planning
- Can be important to incorporate speed decisions also in routing and scheduling (also for environmental reasons)


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Inventory routing*

- Combining inventory management with ship routing and scheduling
- No defined cargoes with a given quantity and time window (laycan)
- Cargoes to be decided (based on inventory levels) together with routing and scheduling decisions


* Andersson, Christiansen and Fagerholt (2009) Transportation planning and inventory management in the LNG supply chain. Accepted for publication in *Energy, Natural Resources and Environmental Economics,* Springer.
Other considerations in the planning

- Soft time windows*
- Split loads**
- Routing choices
  - E.g. Suez canal or via Cape Good Hope
- Considering uncertainty, robustness
  - Modelling of market opportunities (TC and spot cargo rates fluctuates over time)
  - Sailing time and time spent in ports
- Etc.


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- Ship routing and scheduling problems are complex
- Manual planning methods most often used by shipping companies
- Significant improvements in solutions can be achieved by using modern optimization-based decision support systems
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