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Publication date: 2018

Document Version Peer reviewed version

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Main reference

Flex Serv Manuf J
https://doi.org/10.1007/s10696-018-9308-z

The profit maximizing liner shipping problem with flexible frequencies: logistical and environmental considerations

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A synthesis of work on

• A recent MSc. thesis at DTU*
• Air emissions from ships (mainly GHGs)
• Speed optimization in maritime transport

FOCUS: CONTAINER SHIPPING

A tactical level ‘fixed route’ problem

- Assumes a fleet of $N$ identical containerships deployed on a given fixed route
  - Can be generalized to non-identical ships

**WHAT IS OPTIMIZED?**
- Maximize the average per day profit of the carrier.
- Any route topology can be examined
OVERVIEW

Model examines

Effect of:

• Bunker price
• Freight rates
• In transit cargo inventory costs

Effect on:

• Ship speeds
• Number of ships
• Service frequency
OVERVIEW

Model examines

Effect of:

• Bunker price
• Freight rates
• In transit cargo inventory costs

Effect on:

• Ship speeds
• Number of ships
• Service frequency

ALSO:

• Profits
• CO2 emissions
Problem inputs

- The route geometry, represented by a set of ports and a set of legs representing the route.
- The lengths of each leg of the route.
- The freight rate of transporting a TEU from a port on the route to another port on the route, for all relevant port pairs (assumed exogenous).
- The demand in TEUs from a port on the route to another port on the route, for all relevant port pairs.
- The bunker price.
- The daily operating costs of each vessel, other than fuel.
- The daily at sea fuel consumption function as a function of ship speed.
- The daily at port fuel consumption.
- The average monetary value of ship cargo on each leg of the route.
- The operator’s annual cost of capital.
- The time spent at each port.
- The cargo handling cost per TEU.
- The capacity of each vessel.
- The minimum and maximum allowable ship speeds.
Main decision variables: 3

• Number of ships $N$ deployed on the route.
• Ship speeds along each leg of the route.
• Service frequency.

NOTE: service frequency is typically assumed FIXED (and typically ONCE A WEEK)

IN OUR MODEL it is allowed TO VARY (be a decision variable)
Mathematical formulation

\[ \hat{\pi} = \text{Max}_{\nu_i \leq N} \left\{ \frac{1}{t_0} \left( \sum_{x} \sum_{z} F_{xz} c_{xz} - P \sum_{i} f(v_i) \frac{L_i}{24v_i} - PA \sum_{j} G_j - \sum_{l} \alpha_i C_i \frac{L_i}{24v_i} - H \sum_{j} D_j \right) - NE \right\} \]

subject to the following constraints:

\[ v_{\min} \leq v_i \leq v_{\max} \quad i \in I \]

\[ Nt_0 = \sum_{i} \frac{L_i}{24v_i} + \sum_{j} G_j \]

and

\[ N \in \mathbb{N}^+ \]
Mathematical formulation

\[ \hat{\pi} = \max_{v_{i}, t_{0}, N} \left\{ \frac{1}{t_{0}} \left( \sum_{x} \sum_{z} F_{zx} c_{zx} - P \sum_{i} f(v_{i}) \frac{L_{i}}{24v_{i}} - PA \sum_{j} G_{j} - \sum_{i} x_{i} C_{i} \frac{L_{i}}{24v_{i}} + H \sum_{j} D_{j} \right) - NE \right\} \]

subject to the following constraints:

\[ v_{min} \leq v_{i} \leq v_{max} \quad i \in I \]  

\[ Nt_{0} = \sum_{i} \frac{L_{i}}{24v_{i}} + \sum_{j} G_{j} \]  

and

\[ N \in \mathbb{N}^+. \]
Key equation

\[ N_{t_0} = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \]
Key equation- inputs

\[ Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \]

Route leg lengths

Port times
Key equation - decision variables

\[ Nt_0 = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \]

- # ships
- Service period (=1/frequency)
- Speeds at legs
1st Observation

• If frequency of service is **FIXED** (eg, service once a week), line has **ONE** degree of freedom: it can only play with N (number of ships) and the speeds.

• One degree of freedom will generally **restrict the feasible solution space** and will generally **entail a cost**.

• If on the other hand service frequency is **FLEXIBLE**, a wider set of alternatives may be available to the line, and these may be more profitable.
2nd observation:
BOTH obj. fcn. and constraints are NONLINEAR

\[ \hat{\pi} = \text{Max}_{v_1, \ldots, v_N} \left\{ \frac{1}{l_0} \left( \sum_x \sum_z F_{zx} c_{zx} - P \sum_t f(v_t) \frac{L_i}{24v_i} - PA \sum_j G_j - \sum_i \alpha_i C_i \frac{L_i}{24v_i} - H \sum j D_j \right) - NE \right\} \]

subject to the following constraints:

\[ v_{\min} \leq v_i \leq v_{\max} \quad i \in I \]

\[ N_l(t_0) = \sum_i \frac{L_i}{24v_i} + \sum_j G_j \]

and

\[ N \in \mathbb{N}^+. \]
Objective function is a ratio

- MAXIMIZE
  \[
  \text{TOTAL ROUTE PROFIT} / \text{ROUTE DURATION}
  \]

- Both numerator and denominator are nonlinear functions of ship speed

- And so is the ratio itself
Linearization

• Follow approach by Wang and Meng (2012)

• Obtain piecewise linear approximation

• Code in MATLAB

• Use Excel Solver

Figure 4.134: Example of the piecewise linear function in MATLAB
Scenario examined

Mainlane East–West

3 main lanes
• Transpacific lane counts for 46% of the overall container trade on the East-West route
• Europe-Asia lane counts for 41% of the trade
• Transatlantic lane counts for 13% of the trade (UNCTAD, 2016).

Fig. 4 Container flows on Mainlane Eas–West route [million TEUs], 2015. WB: westbound, EB: eastbound. Adapted from UNCTAD (2016), Table 1.7
Trade imbalances

Fig. 3  Trade imbalances between Far East and Europe. The vertical line in 4Q08 is the repeal of EU Regulation 4056/86 in 2008. Source FMC (2012)
Freight rate imbalances

Fig. 2 Freight rate imbalances between Asia and the US. The vertical line in 4Q08 is the repeal of EU Regulation 4056/86 in 2008. Source FMC (2012)
Routes examined

- **AE2**: North Europe and Asia: such service links Asia to North Europe and is provided by Maersk. The same service is also provided by MSC under the name SWAN.

- **NEUATL1**: North Europe and North America (East Coast): links North Europe to the US East Coast. The service is furnished by MSC or similarly by Maersk under the name TA1.

- **TP1**: North America (West Coast) and Asia: the route connects Asia to the West Coast of North America. Maersk offers this service. Same service is also provided by MSC and it is called EAGLE.
<table>
<thead>
<tr>
<th>Ports</th>
<th>AE2</th>
<th>TP1</th>
<th>NEUATL1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Felixstowe</td>
<td>1</td>
<td>1</td>
<td>Antwerp</td>
</tr>
<tr>
<td>Antwerp</td>
<td>2</td>
<td>2</td>
<td>Rotterdam</td>
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<tr>
<td>Wilhelmshaven</td>
<td>3</td>
<td>3</td>
<td>Bremerhaven</td>
</tr>
<tr>
<td>Bremerhaven</td>
<td>4</td>
<td>4</td>
<td>Norfolk</td>
</tr>
<tr>
<td>Rotterdam</td>
<td>5</td>
<td>5</td>
<td>Charleston</td>
</tr>
<tr>
<td>Colombo</td>
<td>6</td>
<td>6</td>
<td>Miami</td>
</tr>
<tr>
<td>Singapore</td>
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<tr>
<td>Hong Kong</td>
<td>8</td>
<td>8</td>
<td>Norfolk</td>
</tr>
<tr>
<td>Yantian</td>
<td>9</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Xingang</td>
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<td></td>
<td></td>
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<td>Qingdao</td>
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<td></td>
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<td>Shanghai</td>
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<td>Tanjung Pelepas</td>
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<tr>
<td>Algeciras</td>
<td>17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sources of data

- UNCTAD [www.unctad.org](http://www.unctad.org) for general information on liner shipping statistics
- EQUASIS (2015), database with information on the world merchant fleet in 2015
- FMC (2012) for transport demand tables, capacity utilization on various trade lanes
- Drewry (2015) for miscellaneous vessel operating cost information
- Maersk Line [www.maersk.com](http://www.maersk.com) for information on routes and schedules including port times
- [https://shipandbunker.com/prices](https://shipandbunker.com/prices) for bunker price information
- [www.shipowners.dk/en/services/beregningsvaerktoejer](http://www.shipowners.dk/en/services/beregningsvaerktoejer), for the SHIP DESMO spreadsheet that calculates fuel consumption and emissions as a function of speed-developed for Danish Shipping
- [www.worldfreightrates.com](http://www.worldfreightrates.com) for freight rate information
- [www.searates.com](http://www.searates.com) for distances among ports
- [www.marinetraffic.com](http://www.marinetraffic.com) for information on ship deadweight, length overall and breadth
- [www.containership-info.com](http://www.containership-info.com) for information on ship power.
3 scenarios

<table>
<thead>
<tr>
<th>#Ships</th>
<th>Speeds</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>• No. 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• No. 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• No. 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 3 scenarios

<table>
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<tr>
<th>#Ships</th>
<th>Speeds</th>
<th>Frequency</th>
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<tbody>
<tr>
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<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>• No. 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• No. 3</td>
<td></td>
<td></td>
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</tbody>
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3 scenarios

<table>
<thead>
<tr>
<th>#Ships</th>
<th>Speeds</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>No. 2</td>
<td>fixed</td>
<td>variable</td>
</tr>
<tr>
<td>No. 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 3 scenarios

<table>
<thead>
<tr>
<th>#Ships</th>
<th>Speeds</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>• No. 1 variable</td>
<td>variable</td>
<td>fixed</td>
</tr>
<tr>
<td>• No. 2 fixed</td>
<td>variable</td>
<td>variable</td>
</tr>
<tr>
<td>• No. 3 variable*</td>
<td>variable</td>
<td>variable</td>
</tr>
</tbody>
</table>

*with an upper bound
1st KEY FINDING

FREQUENCY OF ONE CALL PER WEEK NOT NECESSARILY OPTIMAL

Requiring frequency to be one call per week may restrict feasible solution space and will generally entail a cost.

Set of allowable service periods (days):

\[ S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\} \]
Flexible frequencies

\[ S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\} \]
Flexible frequencies

• $S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\}$

• (weekly service)
Flexible frequencies

- $S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\}$

- (biweekly service)
Flexible frequencies

• $S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\}$

• (twice a week service)
Flexible frequencies

\[ S = \{3.5, 4, 5, 6, 7, 8, 9, 10, 14\} \]

• ???

• (this week Sunday, next week Saturday, following week Friday, etc)
**Fig. 8** Fixed number of ships scenario, optimal service period and optimal average speed at different average freight rates (route TP1)
**Fig. 10** Number of ships bounded above scenario, optimal service period and optimal average speed at different bunker prices (route AE2)
Cost of forcing a weekly frequency

<table>
<thead>
<tr>
<th>Instance</th>
<th>Average freight rate (USD/TEU)</th>
<th>Optimal $t_0$ (days)</th>
<th>$\Delta$ (USD/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>393</td>
<td>8</td>
<td>4,132</td>
</tr>
<tr>
<td>2</td>
<td>429</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>572</td>
<td>6</td>
<td>15,717</td>
</tr>
<tr>
<td>4</td>
<td>644</td>
<td>6</td>
<td>35,029</td>
</tr>
<tr>
<td>5</td>
<td>715</td>
<td>6</td>
<td>54,341</td>
</tr>
<tr>
<td>6</td>
<td>787</td>
<td>6</td>
<td>73,653</td>
</tr>
<tr>
<td>7</td>
<td>858</td>
<td>6</td>
<td>92,965</td>
</tr>
<tr>
<td>8</td>
<td>1,001</td>
<td>6</td>
<td>131,590</td>
</tr>
</tbody>
</table>
Explanation

Low freight rates

• Enforcing a weekly frequency (higher than the optimal one)
  – Requires a speed higher than the optimal one
  – Increased revenue is lower than increased cost

High freight rates

• Enforcing a weekly frequency (lower than the optimal one)
  – Requires a speed lower than the optimal one
  – Reduced revenue is higher than reduced cost
Can flexible frequencies work?

• As things stand today, NO WAY!

• BUT!

• Why not?
Can flexible frequencies work?

• As things stand today, NO WAY!

• BUT!

• Why not?

• Is weekly freq. in the Bible?

• Is weekly freq. mandated by law?

• Or is it just the force of habit?
Fig. 13  Comparison between the $N$ limited scenario and the $N$ unlimited scenario, effect of the bunker price on the daily CO$_2$ emissions (route AE2)
Fig. 15  Effect of inventory costs and bunker price on the optimal speeds (route AE2). The speeds are higher on the legs on which the daily inventory costs are higher.
PARENTHESIS

IMO GHG discussion

• Chile and Peru objected to "speed reduction" as a measure.
• Argued that sending cherries to China would suffer.
• Suggested using "speed optimization" instead

Compromise solution

• Both "speed optimization" and "speed reduction" were included in the text
IMO wording

.4 consider and analyse the use of speed optimization and speed reduction as a measure, taking into account safety issues, distance travelled, distortion of the market or trade and that such measure does not impact on shipping's capability to serve remote geographic areas;

• But no one is really sure what is meant by “speed optimization”!
A look at the facts

Source: ShipCLEAN project (2018)

**EASTBOUND:** Xiamen, Ningbo, Shanghai, Manzanillo, Buenaventura, Callao, San Antonio

**WESTBOUND:** Callao, Manzanillo, Kaohsiung, Yantian, Hong Kong, Xiamen
Observation: **Speed reduction BIG TIME**

Source: ShipCLEAN project (2018)

**EASTBOUND:** Xiamen, Ningbo, Shanghai, Manzanillo, Buenaventura, Callao, San Antonio

**WESTBOUND:** Callao, Manzanillo, Kaohsiung, Yantian, Hong Kong, Xiamen
Conclusions

• Optimization of logistics services can play an important role in emissions reduction
• Under certain circumstances, win-win scenarios can be realized
• A fixed service frequency is not necessarily optimal in liner shipping
• Tools like this can be used to explore logistical measures to reduce CO2
Recent papers

Marit Econ Logist
https://doi.org/10.1057/s41278-018-0098-8

Decarbonization of maritime transport: to be or not to be?

Harilaos N. Psaraftis¹
Recent papers ii


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Invited Review

The role of operational research in green freight transportation

Tolga Bektaş\textsuperscript{a,\ast}, Jan Fabian Ehmke\textsuperscript{b}, Harilaos N. Psaraftis\textsuperscript{c}, Jakob Puchinger\textsuperscript{d,e}
Thank you very much!

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