Design and Analysis of Container Liner Shipping Networks

Rommert Dekker, Judith Mulder

Erasmus School of Economics, Rotterdam, The Netherlands
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• Liner shipping

• Liner shipping Networks

• Network optimization

• Indonesia case
Demand for shipping

- Usually global trade increases 2-3 times the global GDP increase. Same holds for container shipping.
Basic modes of operation in shipping

• **Industrial shipping**
  – Shipper (cargo owner) controls the fleet of vessels (owned or on TC)
  – Must ship the total demand while minimizing costs
  – Decisions: Routing and scheduling
  – Vertically integrated companies

• **Tramp shipping**
  – Combination of contract and optional spot cargoes
  – Ships follow the available cargoes, similar to a taxi service
  – Decisions: Routing/scheduling and selection of spot cargoes
  – Maximize profit

• **Liner shipping**
  – Ships follow a published schedule, similar to a bus line
  – Container, ro-ro and general cargo vessels
Liner Shipping Planning Levels

Strategic planning (long term)
Acquire resources, determine fleet size and mix

General policies and guidelines

Revenue and cost information

Tactical planning (medium term)
Design the service network (frequency of routes, port selection, port rotation), assign ships to routes

Goals, rules, and limits

Revenue and cost information

Operational planning (short term)
Choose which cargo to accept/reject for routing, route the selected cargo

Simultaneous ship-scheduling and cargo-routing problem

Figure 2 Planning Levels for Liner Shipping

Agarwal and Ergun TS (2008)
Difference shipping and other modes

• Cargo differs from passengers: passengers transfer by themselves, cargo needs to be handled: costly

• Passengers want short transfer connections: cargo may wait

• Ships operate 24/7, trains often not and planes are often not only allowed to take off / land during night

• Ships may vary speed and have to follow continents and important passages (Panama, Suez canals) Port calls are rather easily changed
Liner Shipping Networks

- Route and schedule published every half year
- Split up per trade lane: Europe – Asia, Intra-Asia, EU- US, etc
- Regularly small changes, yet important for ports!
- Big changes in case of crises (closure Suez Canal, pirates)
Example ship string NYK line EU2
Liner network optimization - elements

- Demand O/D (origin / destination) matrix
- Cost structure
- Network / Route structure
- Vessel type
- Sailing frequency, speed, call restrictions
Case Intra - Indonesia connections

- The government of Indonesia wants to support cheap and frequent container connections between its main islands.

- A study was done by Drewry Shipping on the best liner shipping network

- We redid some parts of the study to test our methods.
**Figure 1.1:** Location of six main ports in Indonesia

<table>
<thead>
<tr>
<th></th>
<th>Belawan</th>
<th>Jakarta</th>
<th>Surabaya</th>
<th>Banjarmasin</th>
<th>Makassar</th>
<th>Sorong</th>
<th>Supply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belawan</td>
<td>-</td>
<td>6500</td>
<td>1000</td>
<td>100</td>
<td>75</td>
<td>25</td>
<td>7700</td>
</tr>
<tr>
<td>Jakarta</td>
<td>6750</td>
<td>-</td>
<td>2000</td>
<td>4000</td>
<td>2800</td>
<td>450</td>
<td>16000</td>
</tr>
<tr>
<td>Surabaya</td>
<td>1000</td>
<td>2500</td>
<td>-</td>
<td>3750</td>
<td>4800</td>
<td>2150</td>
<td>14200</td>
</tr>
<tr>
<td>Banjarmasin</td>
<td>100</td>
<td>3600</td>
<td>3500</td>
<td>-</td>
<td>10</td>
<td>0</td>
<td>7210</td>
</tr>
<tr>
<td>Makassar</td>
<td>100</td>
<td>3500</td>
<td>4000</td>
<td>75</td>
<td>-</td>
<td>0</td>
<td>7675</td>
</tr>
<tr>
<td>Sorong</td>
<td>50</td>
<td>650</td>
<td>2000</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>2700</td>
</tr>
<tr>
<td><strong>Demand</strong></td>
<td>8000</td>
<td>16750</td>
<td>12500</td>
<td>7925</td>
<td>7685</td>
<td>2625</td>
<td>55485</td>
</tr>
</tbody>
</table>

**Table 1.1:** Expected weekly demand in TEU between the Indonesian ports (Source: own calculations)
Cost structure

- Revenue for every transported container (dependent on distance?)

- Shipping costs – dependent on type
  - annualized investment + operation costs:
  - fuel costs dependent on the speed

- Port costs
  - loading, unloading, transshipment of container
  - port call costs
Network / Route structure

Many different types (definitions not precise)

- Prime (Mainline) and Secondary (Feeders) (aggregate small ports)
- Hub and Spoke / Feeder (KLM, Air France, etc)
- Point-to-point network (Easyjet, Ryanair)
- Line network (Dutch Railways)
Point-to-point and hub-and-spoke networks

Point-to-Point

Hub-and-Spoke

Ptp – applied by Ryanair, Easyjet, H&S by KLM, Lufthansa, Emirates.

Source: Jean-Paul Rodrigue, Hofstra University
Shipping route structures

- Hub and feeder system capacity can be adjusted per link. Costly transshipment needed. Congestion in hub
Shipping route structure

- Circular / milkrun route direction is important. One ship type. Transit times can be long. Notice ship direction!

(b) Example of a circular route
Shipping route structures

- Butterfly: one port is visited twice by same ship
More flexibility than circular route, but many more butterfly routes exist than circular routes!
Route structure Pendulum

- Advantage: no transshipment needed, fast links
- Disadvantage: one capacity for all links

Proposed in studies: Pendulum Nusantara
Vessel Sizes: Increasing
Increasing vessel size

First Generation (1956-1970)
- Converted Cargo Vessel: Length 135 m, Draft < 9 m, TEU 500
- Converted Tanker: Length 200 m, TEU 800

- Cellular Containership: Length 215 m, Draft 10 m, TEU 1,000 - 2,500

- Panamax Class: Length 250 m, Draft 11-12 m, TEU 3,000
- Panamax Class: Length 290 m, TEU 4,000

- Post Panamax: Length 275 - 305 m, Draft 11-13 m, TEU 4,000 - 5,000

Fifth Generation (2000-?)
- Post Panamax Plus: Length 335 m, Draft 13-14 m, TEU 5,000 - 8,000
Ships considered in case

- Data is not always certain, various definitions exist in port draft (e.g. actual draft, dredging target draft, published draft, etc).

- Bunker cost about 600 USD per ton – more than the ship costs.

<table>
<thead>
<tr>
<th>Ship</th>
<th>Capacity (TEU)</th>
<th>Cost (USD/day)</th>
<th>Draft (m)</th>
<th>Min speed (knots)</th>
<th>Design speed (knots)</th>
<th>Max speed (knots)</th>
<th>Fuel usage (ton/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>900</td>
<td>5,000</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>18.8</td>
</tr>
<tr>
<td>Type 2</td>
<td>1600</td>
<td>8,000</td>
<td>9.5</td>
<td>10</td>
<td>14</td>
<td>17</td>
<td>23.7</td>
</tr>
<tr>
<td>Type 3</td>
<td>2400</td>
<td>11,000</td>
<td>12</td>
<td>12</td>
<td>18</td>
<td>19</td>
<td>52.5</td>
</tr>
<tr>
<td>Type 4</td>
<td>3500</td>
<td>15,000</td>
<td>12</td>
<td>12</td>
<td>18</td>
<td>20</td>
<td>55.0</td>
</tr>
<tr>
<td>Type 5</td>
<td>4800</td>
<td>21,000</td>
<td>11</td>
<td>12</td>
<td>16</td>
<td>22</td>
<td>57.4</td>
</tr>
</tbody>
</table>

*Table 1.3: Data of the ship characteristics (Source: Brouer et al. 2014a)*
Speed optimization

• Strategic – which engines to use in ships: slow steaming gives a very large CO$_2$ reduction!

• Tactical – choose a speed for a route

• Operational – adapt speed to actual weather and delays encountered on route

In the case: fuel consumption $F_s(v)$, $v$ actual speed, $v_s$ nominal speed, $f_s$ fuel consumption with design speed.

$$F_s(v) = 600 \cdot \left( \frac{v}{v_s^*} \right)^3 \cdot f_s$$
Speed vs fuel consumption of ships

**Figure 1.3:** Fuel cost in USD per nautical mile
Effect of speed reduction on supply chains
Source: Eefsen and Cerup-Simonson (2010)

Figure 10. Transportation costs and CO2 emissions for shipment of a container from Ningbo (China) to Bremerhaven (Germany) on a 6,600 TEU containership at varying speeds. Declared value is 23.5 USD/cu ft and interest rate 35%. Bunker oil price is 480 USD/MT.
Other route restrictions

• Draft restrictions (not really in case, but largest containerships can not reach Hamburg fully laden)

• Frequency optimisation (how often / week)

• Fixed weekly calls – now preferred by shippers coordinates factory processes with shipping

• This led to large scale alliances as for lines lasting 9 weeks 9 ships are necessary and individual shipping lines lacked the number of ships!
Optimization methods

• Long history, but slow development compared to railways and airlines.

• Regular reviews by Roonen, Fagerholt, Christiansen

• Last one by Meng, Wang, Andersson and Thun (2014)

• Theory started from considering sub problems, simple lines, one ship type, to more complex structures.

• Popular approach: create many routes first, then select them and route cargo: allows to “optimize routes”.

Methods for Network Design & Cargo Routing

• Agarwal and Ergun (2008)
  MILP model based on space-time network, integrated ship-scheduling & cargo routing (NP-C)
  Greedy heuristic, column generation and two-phase Benders decomposition algorithm.

  No transhipment costs! Speeds fixed.

• Alvarez (2009)
  extends A&E by incorporating transhipment costs and considered “run” = ship + speed + ports of call”
  Applies Tabu search + column generation
  Problems with 120 ports and 5 ship/speed types.
  No weekly calls
Methods for Network Design

- Meng & Wang (2011) – considered specific network types

- Reinhardt & Pisinger – considered butterfly routes.

- Mulder and Dekker (2013)
  Generate + optimize routes first using Mainport / feeder aggregation,
  evolutionary algorithm for creating main routes
  use LP model for cargo routing and integers for route selection

- Brouer et al. (2014) – benchmark data + model.
Indonesia Case Data

**Costs**

- Revenue of shipping one TEU to destination: $200
- Costs for loading / unloading one TEU $40 per port
- Cost for transhipment: $40
- Port fees: $628 per port visit

**Assumptions**

- Five ship types
- Port draft enough for all these types
- No existing fleet restriction
- Duration of transhipment in port 24 hours (should depend on cargo to be (un)loaded
Methodology (Mulder et al. (2013))

1. Route Generation
2. Determine Optimal Speed per Route
3. Solve Cargo-Allocation model
• Only routes visiting every port at most once are considered (except for the start port). No butterfly routes

• All possible routes between the six ports are generated and duplicated for every ship type

• By enumerating, the total number of route-ship combinations is equal to 2045
• For all routes, the optimal speed is determined, considering both sailing and idle time, while adhering weekly call restrictions.
In the final step a reformulation of the cargo-allocation model, originally presented by Mulder and Dekker [2013], is solved using a path formulation.

- Mixed – Integer-Programming – profit optimization problem (you may choose not to ship all containers) integers for choosing routes

- Complexity increases dramatically by adding new routes
Cargo Routing Model

multi-commodity formulation

\begin{equation}
\max \sum_{h_1 \in \mathcal{H}} \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} r_{h_1, h_2} \left( x_{h_1, h_2, s}^{rd} + \sum_{t \in T} x_{h_1, t, h_2, s}^{rt} \right) - \sum_{h_1 \in \mathcal{H}} c_{h_1}^h \left( \sum_{t \in T} \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} \left[ x_{h_1, t, h_2, s}^{rt} + x_{h_2, t, h_1, s}^{rt} \right] + \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} \left[ x_{h_1, h_2, s}^{rd} + x_{h_2, h_1, s}^{rd} \right] \right)
- \sum_{t_1 \in T} c_{t_1}^t \left( \sum_{h_2 \in \mathcal{H}} \sum_{h_3 \in \mathcal{H}_1} \sum_{s_1, s_2 \in \mathcal{S}} \sum_{s_3 \in \mathcal{S}_3} x_{h_2, t_1, h_3, s_1, s_2, s_3}^{rd} + \sum_{h_2 \in \mathcal{H}} \sum_{s_1, s_2 \in \mathcal{S}} x_{h_2, s_1, s_2}^{rd} \right)
\end{equation}

\begin{equation}
\text{s.t.} \sum_{t \in T} \sum_{s \in \mathcal{S}} x_{h_1, t, h_2, s}^{rt} + \sum_{s \in \mathcal{S}} x_{h_1, h_2, s}^{rd} \leq d_{h_1, h_2} \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H}
\end{equation}

\begin{equation}
x_{h_1, h_2, s} \leq b_s \quad (h_1, h_2, s) \in \mathcal{K}
\end{equation}

\begin{equation}
\sum_{h_1 \in \mathcal{H}} \sum_{h_2 \in \mathcal{H}} \sum_{s_1, s_2 \in \mathcal{S}} x_{h_1, t_1, h_2, s_1}^{rt} + \sum_{t_2 \in T} \sum_{s_1, s_2 \in \mathcal{S}} x_{h_2, t_2, h_3, s_2, s_1}^{rt} - \sum_{s_2 \in \mathcal{S}_2} x_{h_2, s_1, s_2}^{rd} = 0 \quad (t_1, h_2, s) \in \mathcal{J}
\end{equation}

\begin{equation}
x_{h_1, h_2, s} - \sum_{h_3 \in \mathcal{H}} \sum_{h_4 \in \mathcal{H}} x_{h_1, h_4, s}^{rd} \delta_{h_4, h_1, h_2, s} = 0 \quad (h_1, h_2, s) \in \mathcal{K}
\end{equation}

\begin{equation}
x_{h_1, h_2, s_1}^{rt} - x_{h_1, h_2, s_1}^{rd} - \sum_{h_3 \in \mathcal{H}} x_{h_1, h_2, h_3, s_1}^{rt} - \sum_{s_2 \in \mathcal{S}} x_{h_1, h_2, s_2, s_1}^{rd} = 0 \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H}, \ s_1 \in \mathcal{S}
\end{equation}

\begin{equation}
x_{h_1, h_2, s} \geq 0 \quad (h_1, h_2, s) \in \mathcal{K}
\end{equation}

\begin{equation}
x_{h_1, h_2, s}^{rd} \geq 0 \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H}, \ s \in \mathcal{S}
\end{equation}

\begin{equation}
x_{t_1, t_2, h_1, s_1, s_2}^{rt} \geq 0 \quad h \in \mathcal{H}, \ s_1 \in \mathcal{S}, \ (t_1, t_2, s_2) \in \mathcal{J}
\end{equation}

\begin{equation}
x_{t, h_1, s_1, s_2}^{rd} \geq 0 \quad s_1 \in \mathcal{S}, \ (t, h, s_2) \in \mathcal{J}
\end{equation}

\begin{equation}
x_{h_1, t, h_2, s}^{rt} \geq 0 \quad h_2 \in \mathcal{H}, \ (h_1, t, s) \in \mathcal{J}
\end{equation}
Results for best Hub-Feeder network

(a) Utilized capacities in TEU for the hub and feeder system
Results for best circular route

(b) Utilized capacities in TEU for the circular route
Results for best butterfly route

(c) Utilized capacities in TEU for the butterfly route
Results for Pendulum network

Figure 1.5: Pendulum route network

Capacity: 11,800
## Route – ship characteristics

<table>
<thead>
<tr>
<th>Route</th>
<th>Distance (nm)</th>
<th>Duration (weeks)</th>
<th>Frequency (per week)</th>
<th>Required ships</th>
<th>Speed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>2990</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>11.33*</td>
</tr>
<tr>
<td>F2</td>
<td>3632</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>12.61</td>
</tr>
<tr>
<td>F3</td>
<td>1201</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>12.51</td>
</tr>
<tr>
<td>Circular</td>
<td>6476</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>12.27</td>
</tr>
<tr>
<td>Butterfly</td>
<td>6862</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>13.62</td>
</tr>
</tbody>
</table>

**Table 1.4:** Route characteristics for the different ships
## Route – ship frequencies

<table>
<thead>
<tr>
<th>Route</th>
<th>Req. cap. (TEU)</th>
<th>Port calls per week</th>
<th>Av. cap. (TEU)</th>
<th>Cost (USD/week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Type 1</td>
<td>Type 2</td>
<td>Type 3</td>
</tr>
<tr>
<td>F1</td>
<td>18,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>F2</td>
<td>2,700</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>F3</td>
<td>15,600</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>HF-Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circular</td>
<td>28,485</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Butterfly</td>
<td>18,225</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 1.6:** Network cost per week when shipping all demand

Optimal fleet size highly dependent on network structure!
Optimality Results

<table>
<thead>
<tr>
<th>Network</th>
<th>Shipped distance (nm/TEU)</th>
<th>Profit (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub-and-feeder</td>
<td>1433.65</td>
<td>4,467,464</td>
</tr>
<tr>
<td>Circular</td>
<td>3269.79</td>
<td>2,328,879</td>
</tr>
<tr>
<td>Butterfly</td>
<td>2199.65</td>
<td>3,664,212</td>
</tr>
<tr>
<td>Pendulum</td>
<td>996.80</td>
<td>4,948,467</td>
</tr>
<tr>
<td>Optimal</td>
<td>925.21</td>
<td>6,152,105</td>
</tr>
</tbody>
</table>

Table 1.7: Efficiency and profit of the different networks

Note: the average shipped distance for a pure point-to-point network is 836 nm/TEU
“Optimal” network

(a) Route 1  
Capacity: 3,500

(b) Route 2  
Capacity: 1,600

(c) Route 3  
Capacity: 3,500

(d) Route 4  
Capacity: 3,500

Figure 1.6: Optimal route network

Note: route 3 is route 4 reversed!
Discussion

• Problem quickly becomes too large to solve exactly: too many networks, especially if ports are called multiple times

• In circular routes orientation is important transit times can become long

• What should be “good” freight prices?

• How can we allocate costs per route?

• Can we take competition & transit time dependent demand into account?
Conclusions case

• Proposed network quite different from the “Pendulum Nusantara”

• Dual hub structure – Jakarta and Surabaya

• High revenues – should also cover office costs

• Optimisation can improve existing networks, but faster and more comprehensive methods are needed.
Conclusions

• Liner shipping has been lacking application of optimization methods compared to airlines and trucking. Sector is somewhat conservative.

• Quite some research is being done and results are promising.

• Decision support systems are likely to come!

• Many more aspects can be optimized.