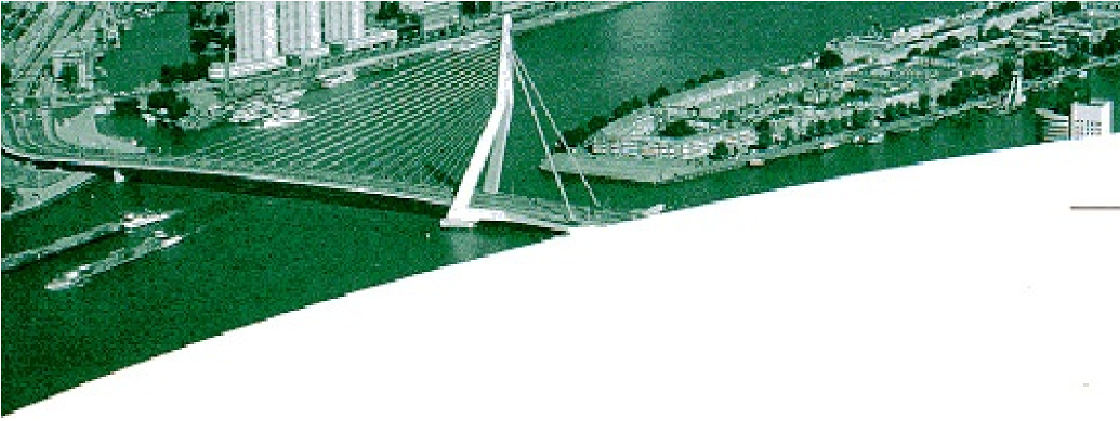

Erasmus Universiteit Rotterdam
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Design and Analysis of Container Liner Shipping Networks

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Contents

- 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

Mostly bulk shipping

Liner Shipping Planning Levels

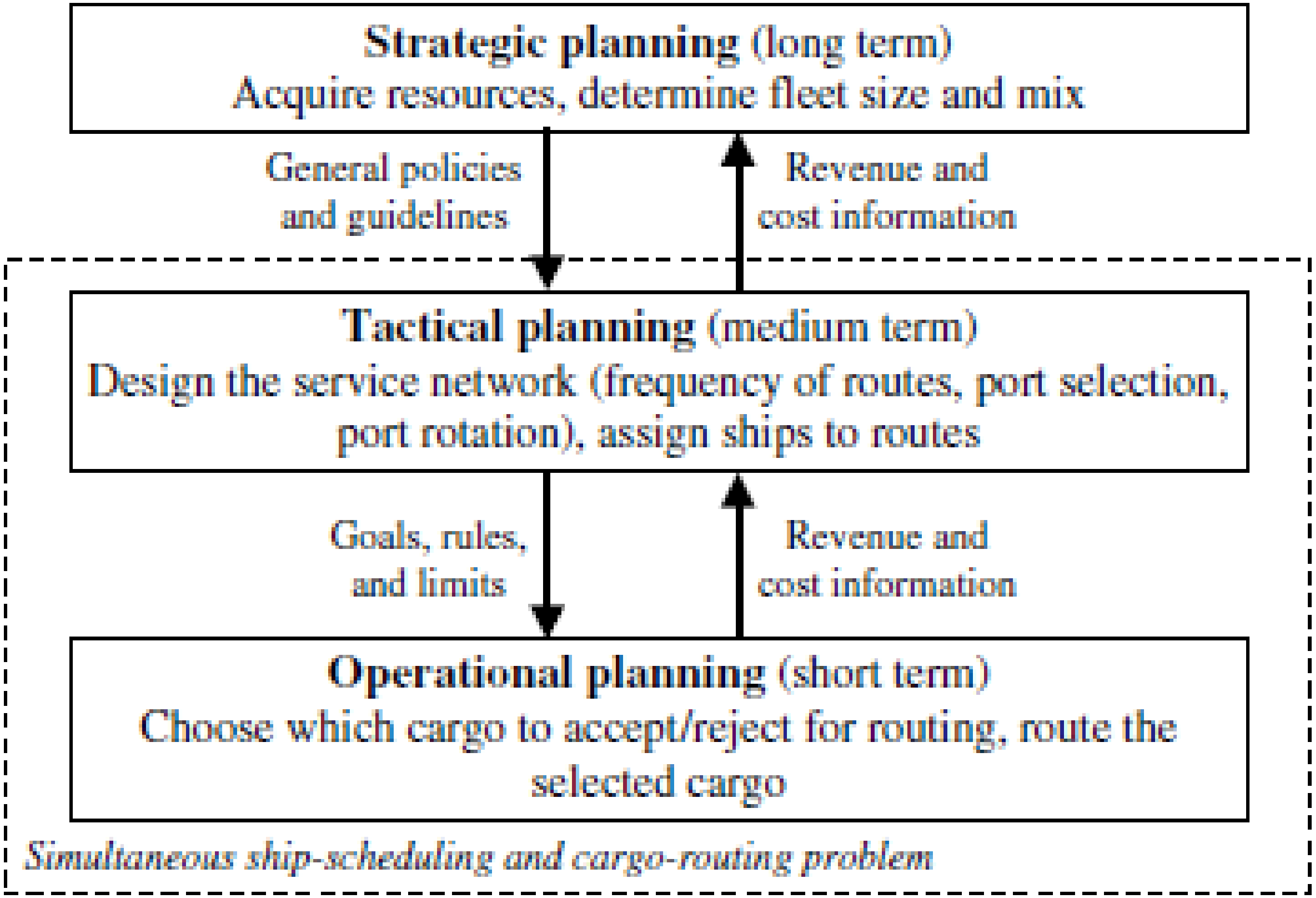


Figure 2 Planning Levels for Liner Shipping

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

NEX EU2: North Europe Express

NEX EMX : NEX EU1 : NEX EU2 : NEX EU3 : NEX EU4 : NEX EU5 : NEX EUM

Port Rotation

Origin	ETA/ETD
Kaohsiung	FRI/SAT
Shekou	SAT/SUN
Yantian	SUN/MON
Hong Kong	MON/TUE
Singapore	FRI/SAT
Le Havre	WED/THU
Amsterdam	FRI/FRI
Hamburg	SAT/MON
Antwerp	TUE/WED
Southampton	THU/FRI
Cagliari	TUE/WED
Jeddah	MON/MON
Jebel Ali	SAT/SUN
Singapore	SUN/MON
Kaohsiung	FRI/SAT

Turnaround days : 63

Weekly/Fixed Day Service

Key Transit Table

W/B	LEH	AMS	HAM	ANR	SOU
KHH	25	27	28	31	33
SHK	24	26	27	30	32
YTN	23	25	26	29	31
HKG	22	24	25	28	30
SIN	18	20	21	24	26

E/B	CAG	JED	JEA	SIN	KHH	SHK	YTN	HKG
LEH	12	18	23	31	36	37	38	39
AMS	11	17	22	30	35	36	37	38
HAM	8	14	19	27	32	33	34	35
ANR	6	12	17	25	30	31	32	33
SOU	4	10	15	23	28	29	30	31
CAG	-	5	10	18	23	24	25	26

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.

Indonesia

Figure 1.1: Location of six main ports in Indonesia

	Belawan	Jakarta	Surabaya	Banjarmasin	Makassar	Sorong	**Supply**
Belawan	-	6500	1000	100	75	25	**7700**
Jakarta	6750	-	2000	4000	2800	450	**16000**
Surabaya	1000	2500	-	3750	4800	2150	**14200**
Banjarmasin	100	3600	3500	-	10	0	**7210**
Makassar	100	3500	4000	75	-	0	**7675**
Sorong	50	650	2000	0	0	-	**2700**
Demand	**8000**	**16750**	**12500**	**7925**	**7685**	**2625**	**55485**

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

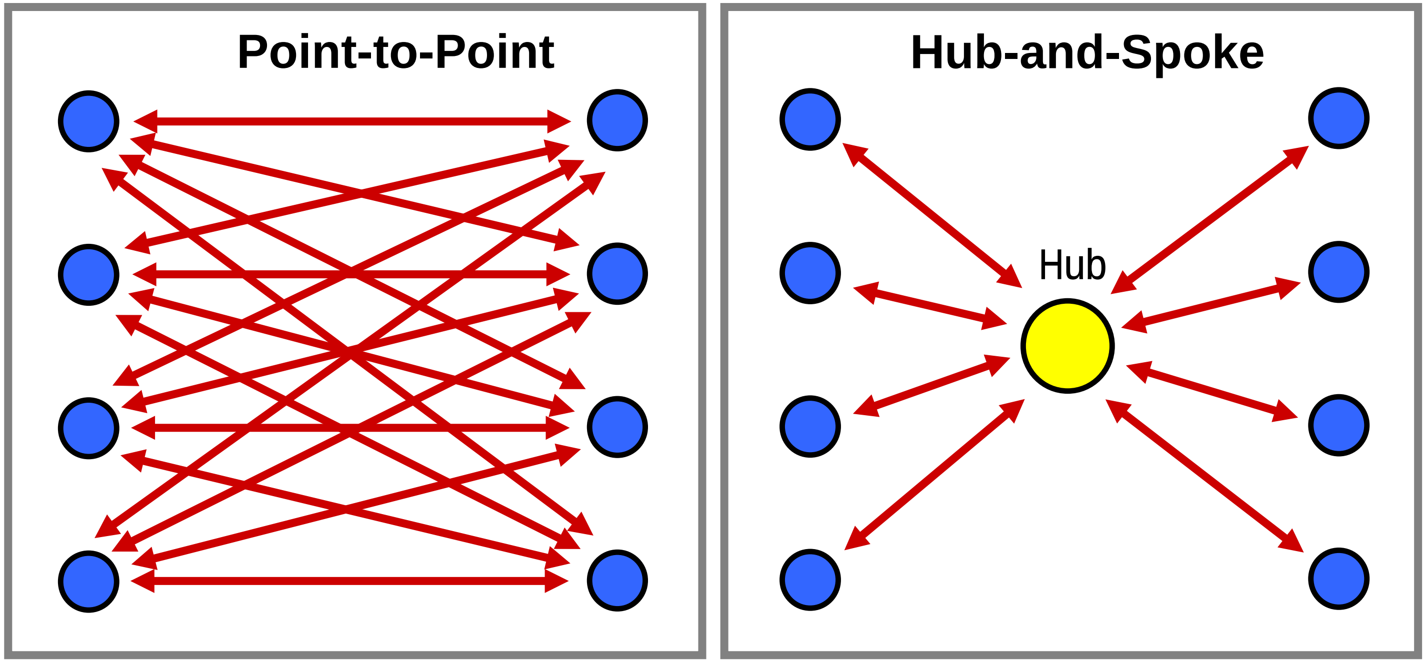
- Port costs
  - loading, unloading, transshipment of container
  - port call costs

Network / Route structure

Many different types (definitions not precise)

- Prime (Mainline) and Secundary (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

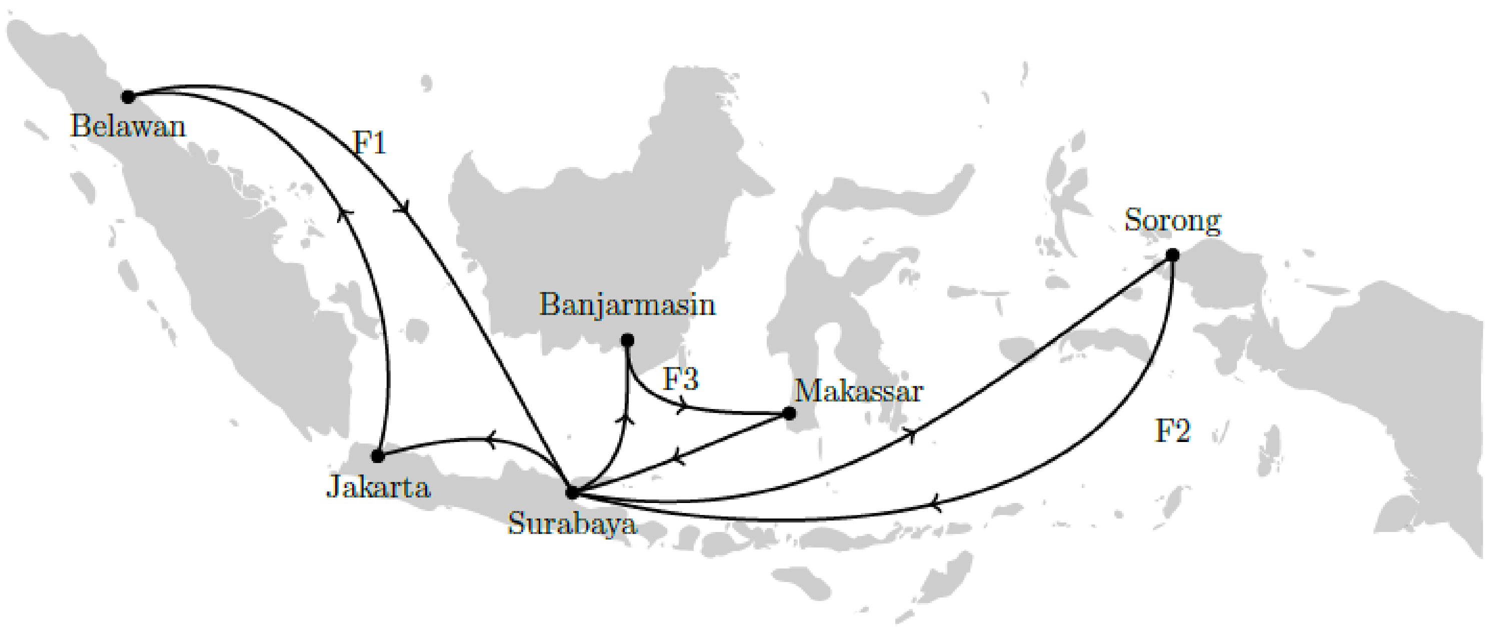


Ptp – applied by Ryanair, Easyjet,
H&S by KLM, Lufthansa, Emirates.

Source: Jean-Paul Rodrigue, Hofstra University

Shipping route structures

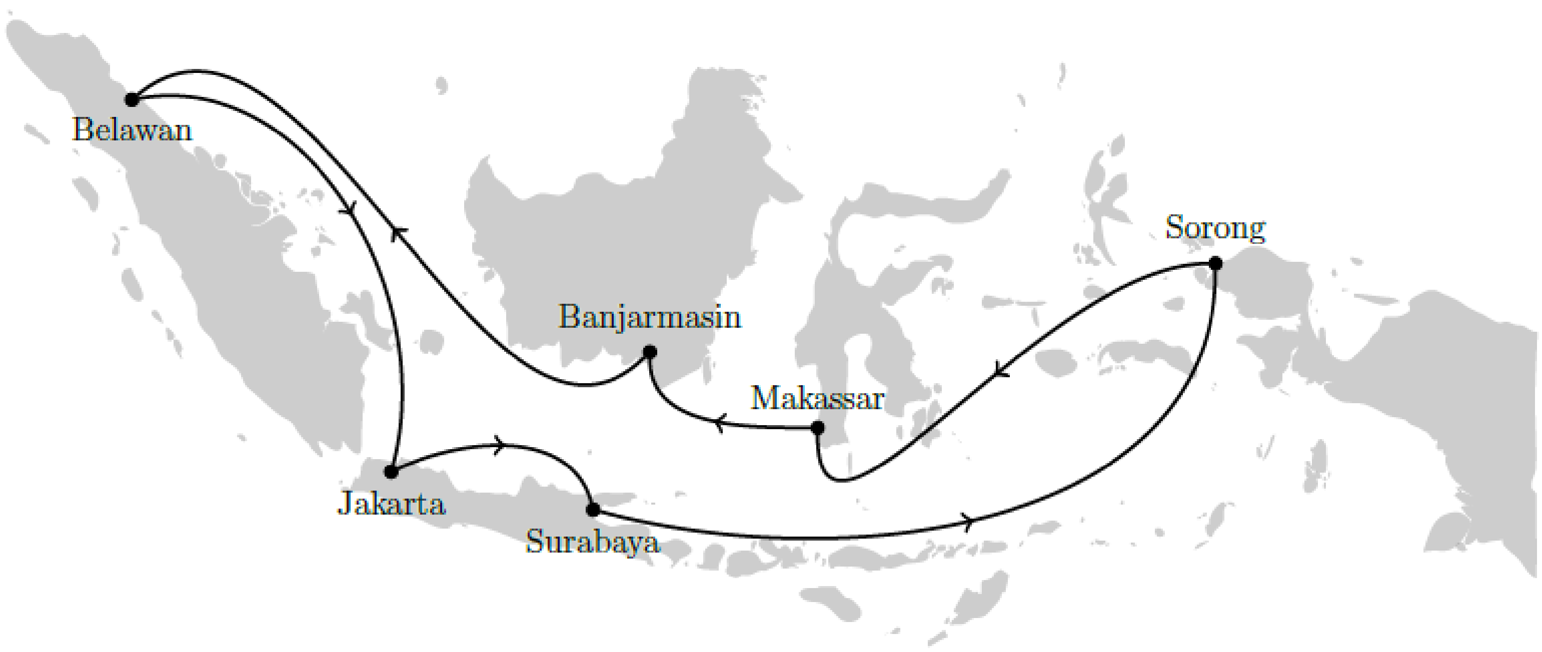
- Hub and feeder system
  capacity can be adjusted per link.
  Costly transshipment needed. Congestion in hub



(a) Example of a hub and feeder system

Shipping route structure

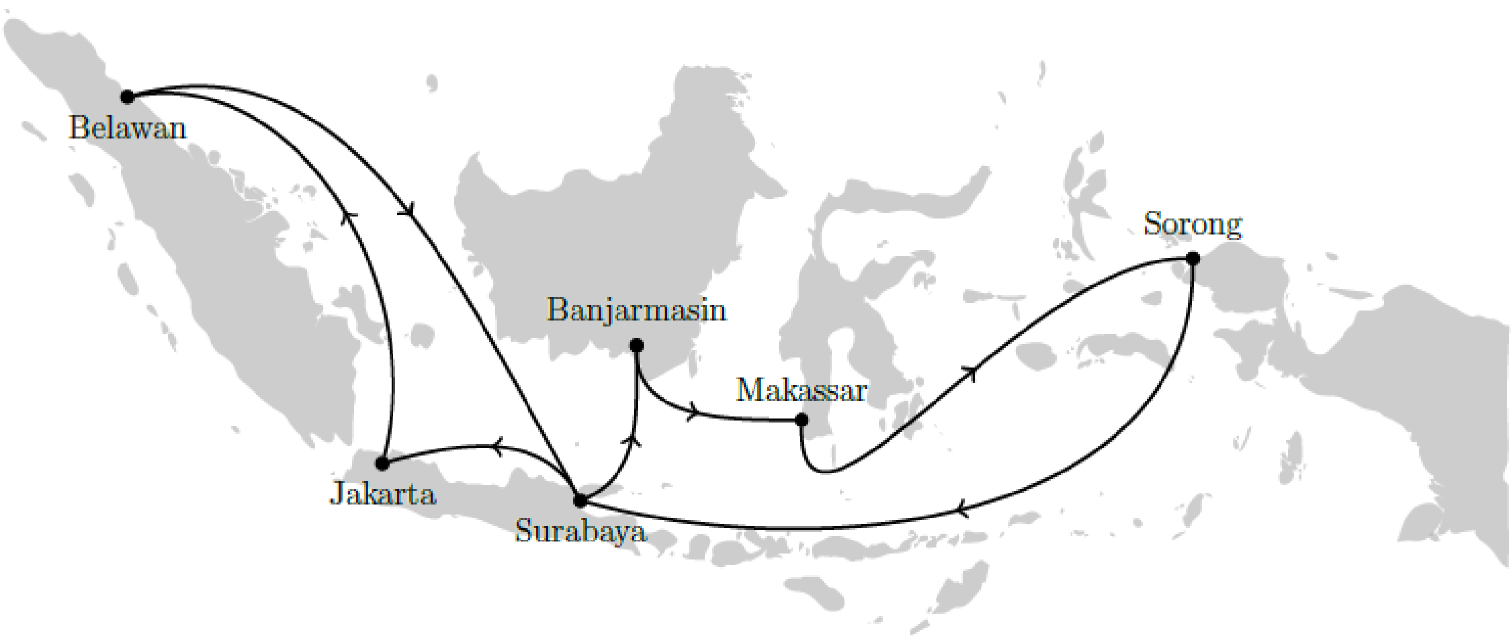
- Circular / milkrun route
  direction is important. One ship type. Transit times can be long. Notice ship direction!



(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!



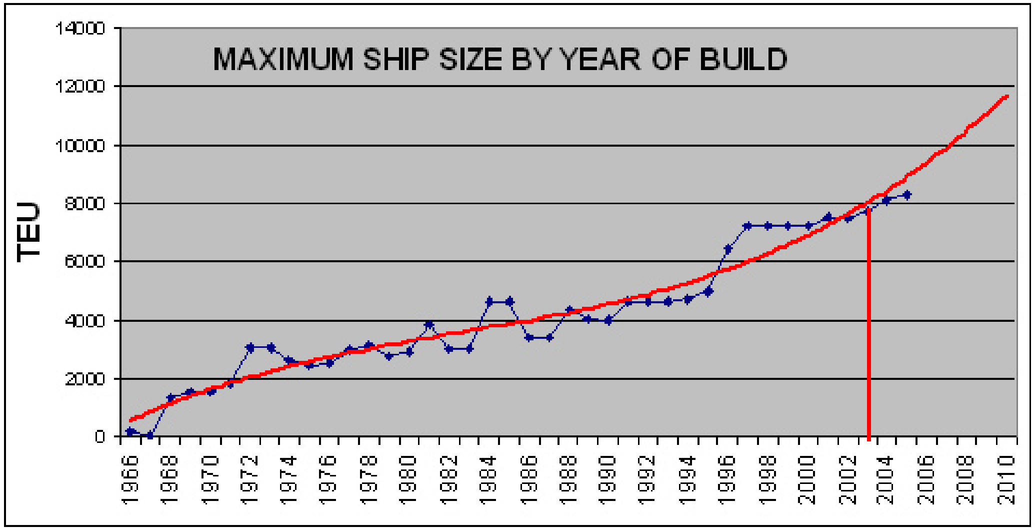
(c) Example of a butterfly route

Route structure Pendulum

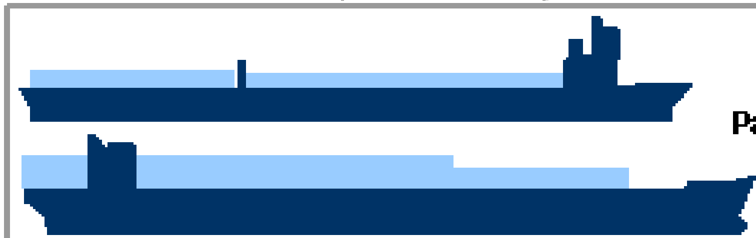
- Advantage: no transshipment needed, fast links
- Disadvantage: one capacity for all links

Proposed in studies: Pendulum Nusantara

Vessel Sizes: Increasing



Increasing vessel size

Generation	Vessel	Length	Draft	TEU
First Generation (1956-1970)	 Converted Cargo Vessel	135 m	< 9 m	500
	 Converted Tanker	200 m		800
Second Generation (1970-1980)	 Cellular Containership	215 m	10 m	1,000 – 2,500
Third Generation (1980-1988)	 Panamax Class	250 m 290 m	11-12 m	3,000 4,000
Fourth Generation (1988-2000)	 Post Panamax	275 – 305 m	11-13 m	4,000 – 5,000
Fifth Generation (2000-?)	 Post Panamax Plus	335 m	13-14 m	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.

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

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

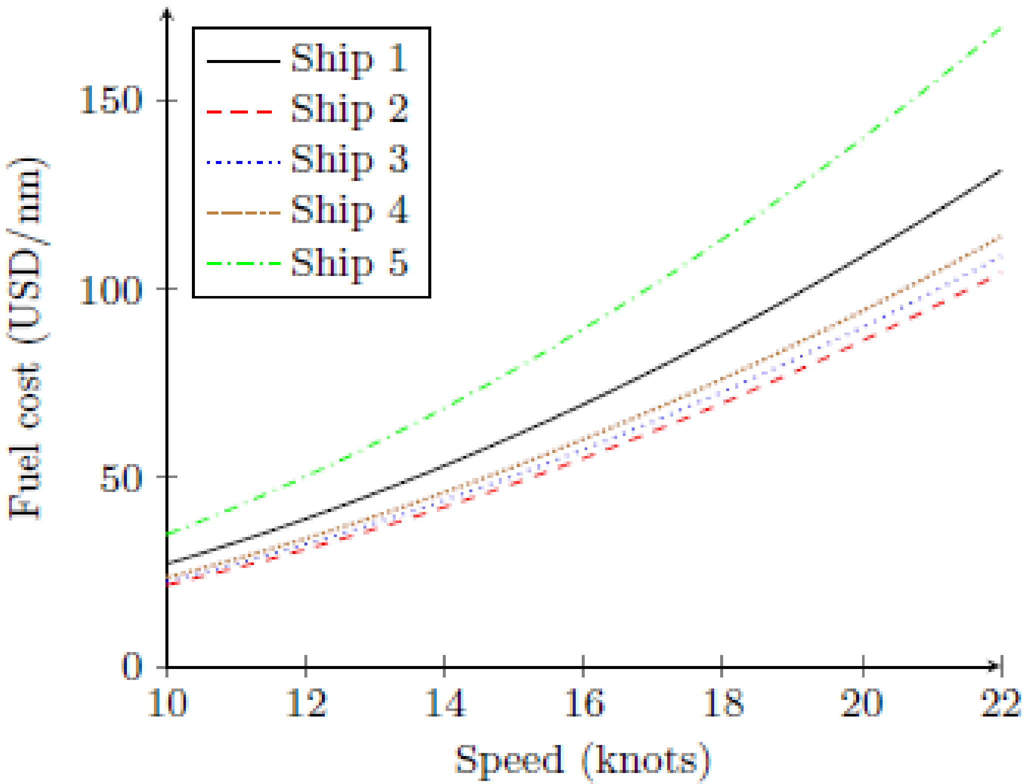
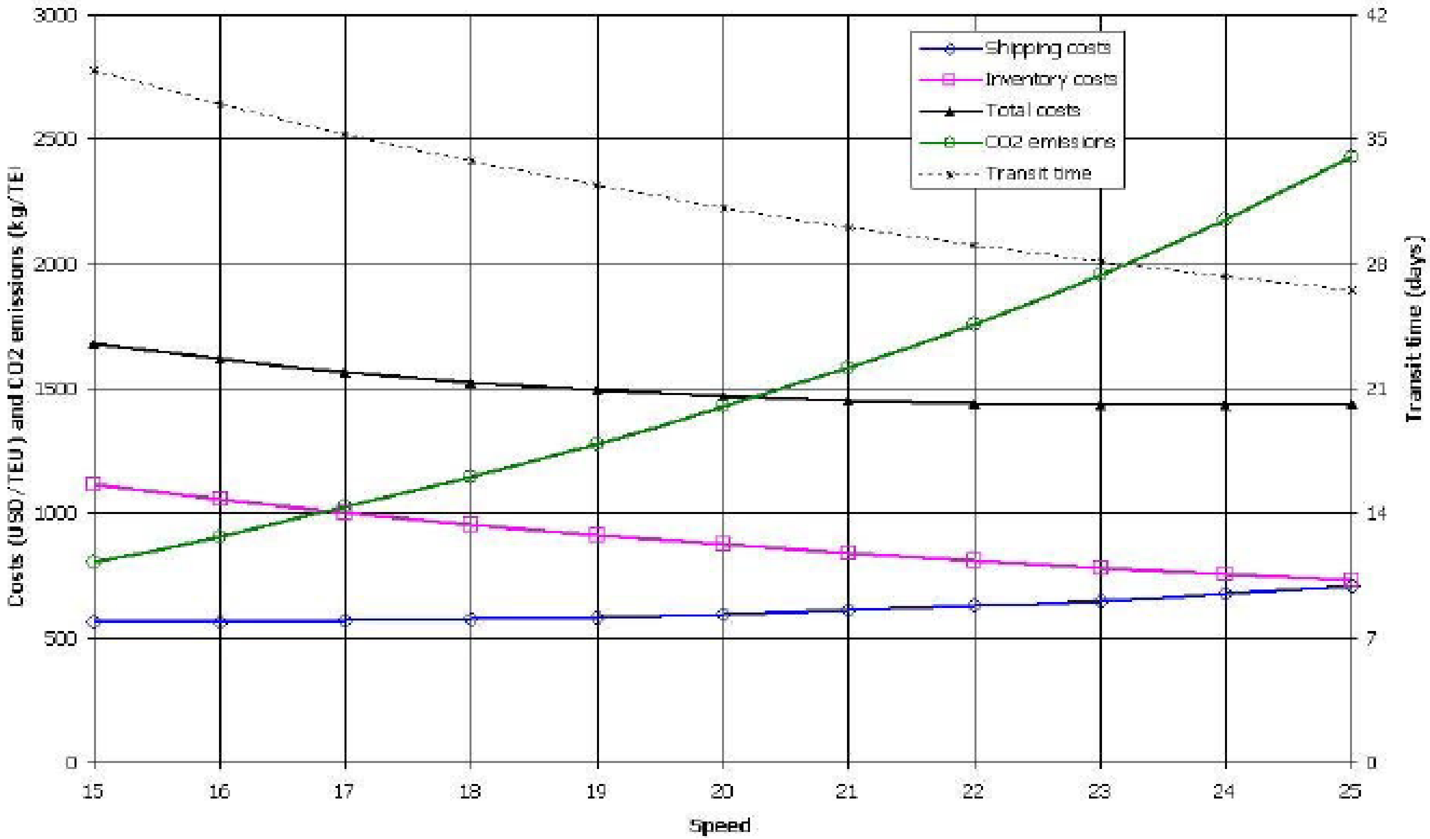


Figure 1.3: Fuel cost in USD per nautical mile

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

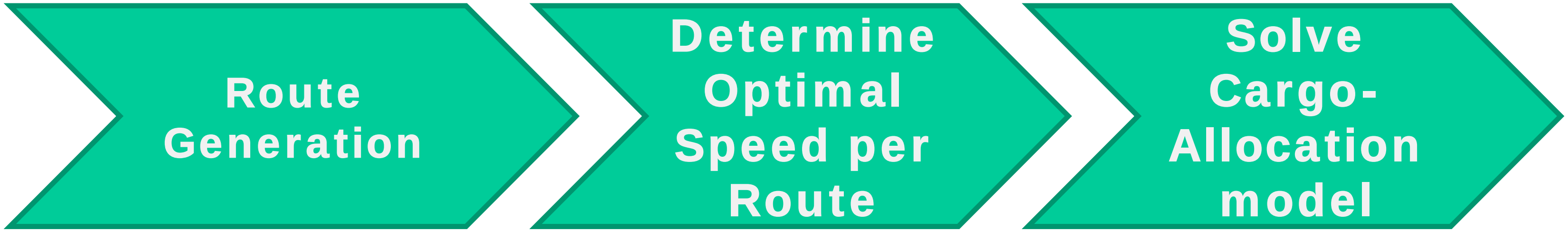
Costs

- 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))



- 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

$h \in \mathcal{H}$	Set of ports.
$t \in \mathcal{T} \subseteq \mathcal{H}$	Set of transhipment ports.
$s \in \mathcal{S}$	Set of ship routes.
$j \in \mathcal{J}$	Indicator set denoting whether a ship passes both ports $h_1 \in \mathcal{H}$ and $h_2 \in \mathcal{H}$ on ship route $s \in \mathcal{S}$, where $j = (h_1, h_2, s)$.
$k \in \mathcal{K}$	Indicator set denoting whether port $h_2 \in \mathcal{H}$ is directly visited after port $h_1 \in \mathcal{H}$ on ship route $s \in \mathcal{S}$, where $k = (h_1, h_2, s)$.

$$\max \sum_{h_1 \in \mathcal{H}} \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} r_{h_1,h_2} \left(x^{od}_{h_1,h_2,s} + \sum_{t \in \mathcal{T}} x^{ot}_{h_1,t,h_2,s} \right)$$
$$- \sum_{h_1 \in \mathcal{H}} c^h_{h_1} \left(\sum_{t \in \mathcal{T}} \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} \left[x^{ot}_{h_1,t,h_2,s} + x^{ot}_{h_2,t,h_1,s} \right] + \sum_{h_2 \in \mathcal{H}} \sum_{s \in \mathcal{S}} \left[x^{od}_{h_1,h_2,s} + x^{od}_{h_2,h_1,s} \right] \right)$$
$$- \sum_{t_1 \in \mathcal{T}} c^t_{t_1} \left(\sum_{t_2 \in \mathcal{T}} \sum_{h_2 \in \mathcal{H}} \sum_{s_1 \in \mathcal{S}} \sum_{s_2 \in \mathcal{S}} x^{tt}_{t_1,t_2,h_2,s_1,s_2} + \sum_{h_2 \in \mathcal{H}} \sum_{s_1 \in \mathcal{S}} \sum_{s_2 \in \mathcal{S}} x^{td}_{t_1,h_2,s_1,s_2} \right) \qquad (1)$$

$$\text{s.t.} \sum_{t \in \mathcal{T}} \sum_{s \in \mathcal{S}} x^{ot}_{h_1,t,h_2,s} + \sum_{s \in \mathcal{S}} x^{od}_{h_1,h_2,s} \leqslant d_{h_1,h_2} \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H} \qquad (2)$$

$$x_{h_1,h_2,s} \leqslant b_s \quad (h_1, h_2, s) \in \mathcal{K} \qquad (3)$$

$$\sum_{h_1 \in \mathcal{H}} x^{ot}_{h_1,t_1,h_2,s_1} + \sum_{t_2 \in \mathcal{T}} \sum_{s_2 \in \mathcal{S}} x^{tt}_{t_2,t_1,h_2,s_2,s_1} - \sum_{s_2 \in \mathcal{S}} x^{td}_{t_1,h_2,s_1,s_2}$$
$$- \sum_{t_2 \in \mathcal{T}} \sum_{s_2 \in \mathcal{S}} x^{tt}_{t_1,t_2,h_2,s_1,s_2} = 0 \quad (t_1, h_2, s) \in \mathcal{J} \qquad (4)$$

$$x_{h_1,h_2,s} - \sum_{h_3 \in \mathcal{H}} \sum_{h_4 \in \mathcal{H}} x^{tot}_{h_3,h_4,s} I^{path}_{h_3,h_4,h_1,h_2,s} = 0 \quad (h_1, h_2, s) \in \mathcal{K} \qquad (5)$$

$$x^{tot}_{h_1,h_2,s_1} - x^{od}_{h_1,h_2,s_1} - \sum_{h_3 \in \mathcal{H}} x^{ot}_{h_1,h_2,h_3,s_1} - \sum_{s_2 \in \mathcal{S}} x^{td}_{h_1,h_2,s_2,s_1}$$
$$- \sum_{h_3 \in \mathcal{H}} \sum_{s_2 \in \mathcal{S}} x^{tt}_{h_1,h_2,h_3,s_2,s_1} = 0 \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H}, \ s_1 \in \mathcal{S} \qquad (6)$$

$$x_{h_1,h_2,s} \geqslant 0 \quad (h_1, h_2, s) \in \mathcal{K} \qquad (7)$$

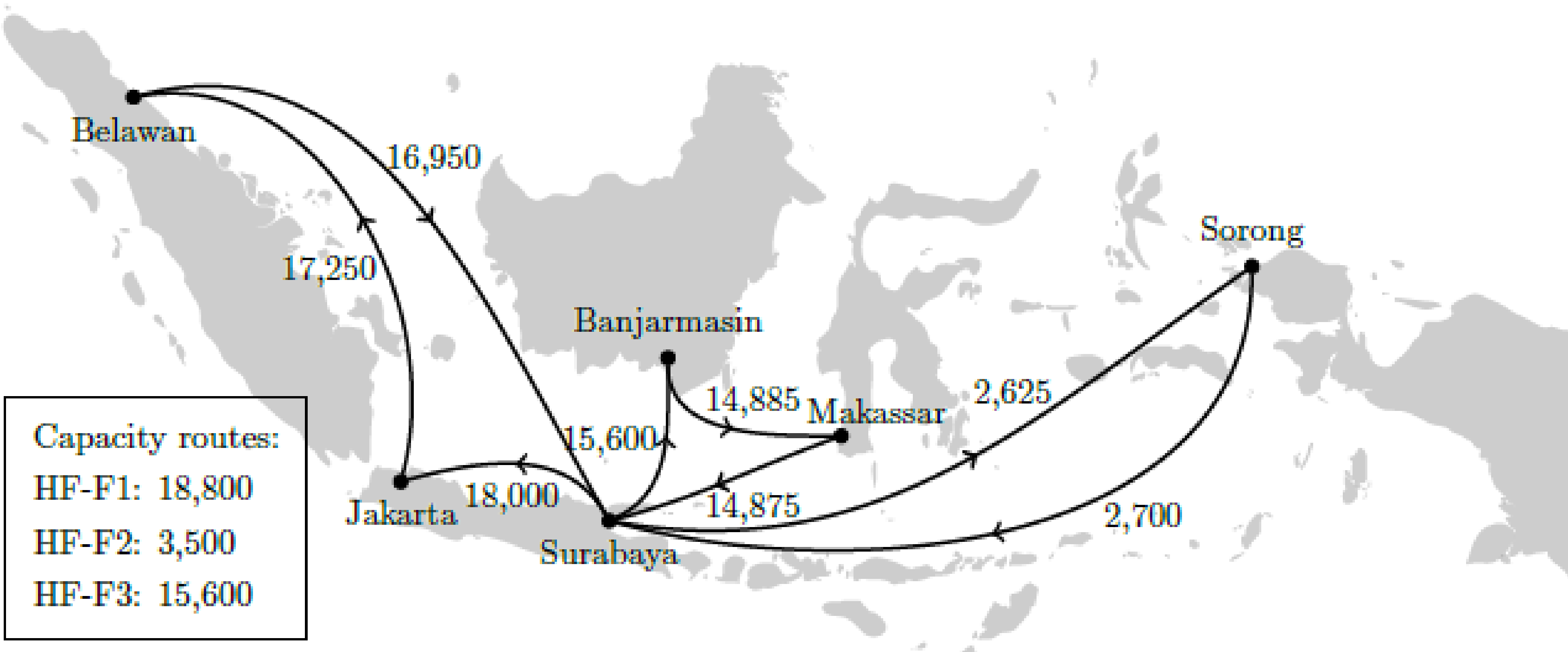
$$x^{od}_{h_1,h_2,s} \geqslant 0 \quad h_1 \in \mathcal{H}, \ h_2 \in \mathcal{H}, \ s \in \mathcal{S} \qquad (8)$$

$$x^{tt}_{t_1,t_2,h,s_1,s_2} \geqslant 0 \quad h \in \mathcal{H}, \ s_1 \in \mathcal{S}, \ (t_1, t_2, s_2) \in \mathcal{J} \qquad (9)$$

$$x^{td}_{t,h,s_1,s_2} \geqslant 0 \quad s_1 \in \mathcal{S}, \ (t, h, s_2) \in \mathcal{J} \qquad (10)$$

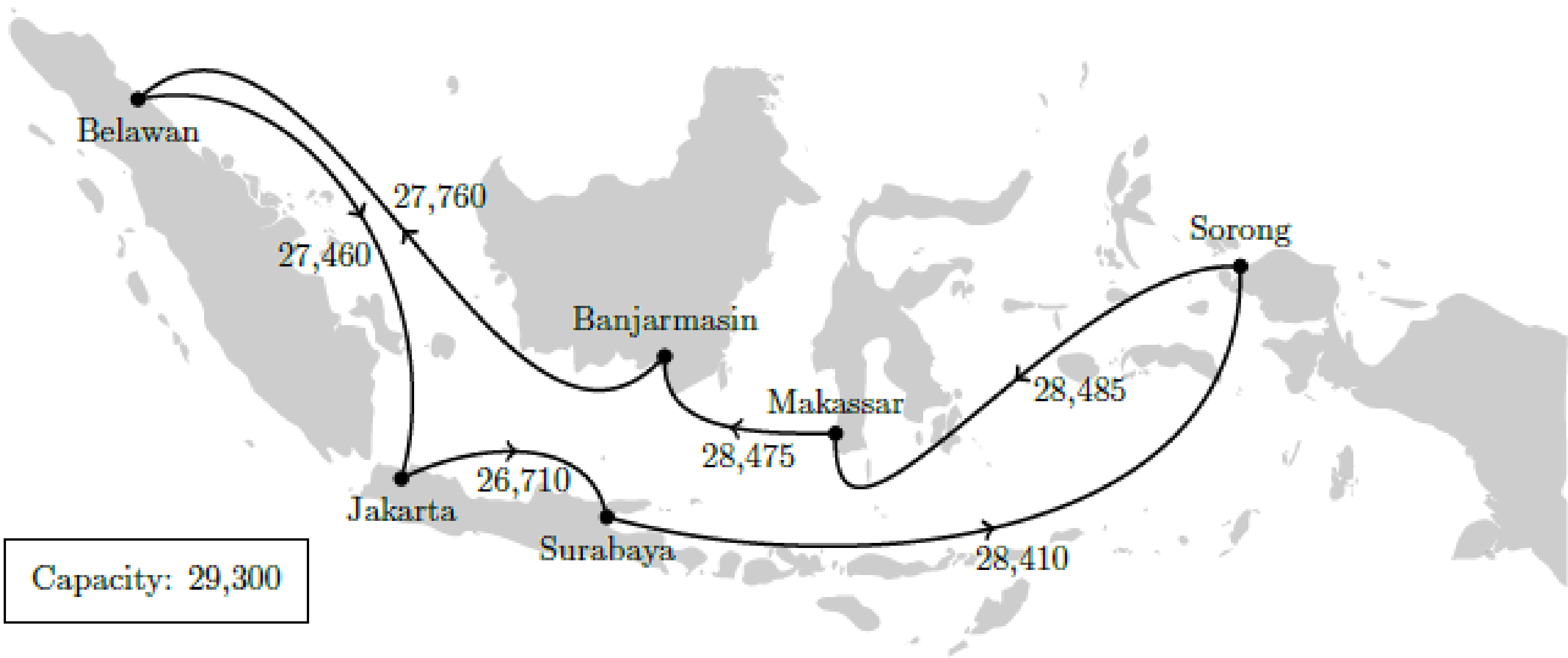
$$x^{ot}_{h_1,t,h_2,s} \geqslant 0 \quad h_2 \in \mathcal{H}, \ (h_1, t, s) \in \mathcal{J} \qquad (11)$$

Results for best Hub-Feeder network



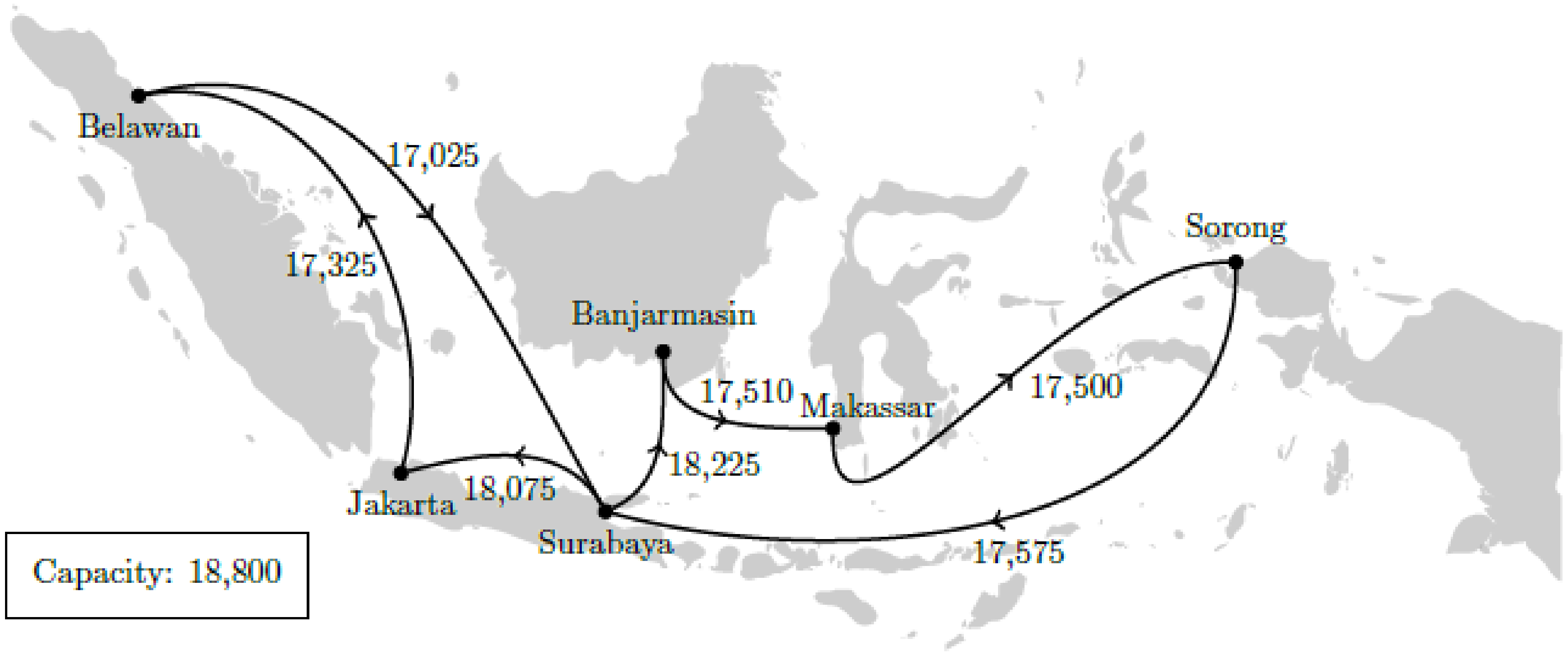
(a) Utilized capacities in TEU for the hub and feeder system

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

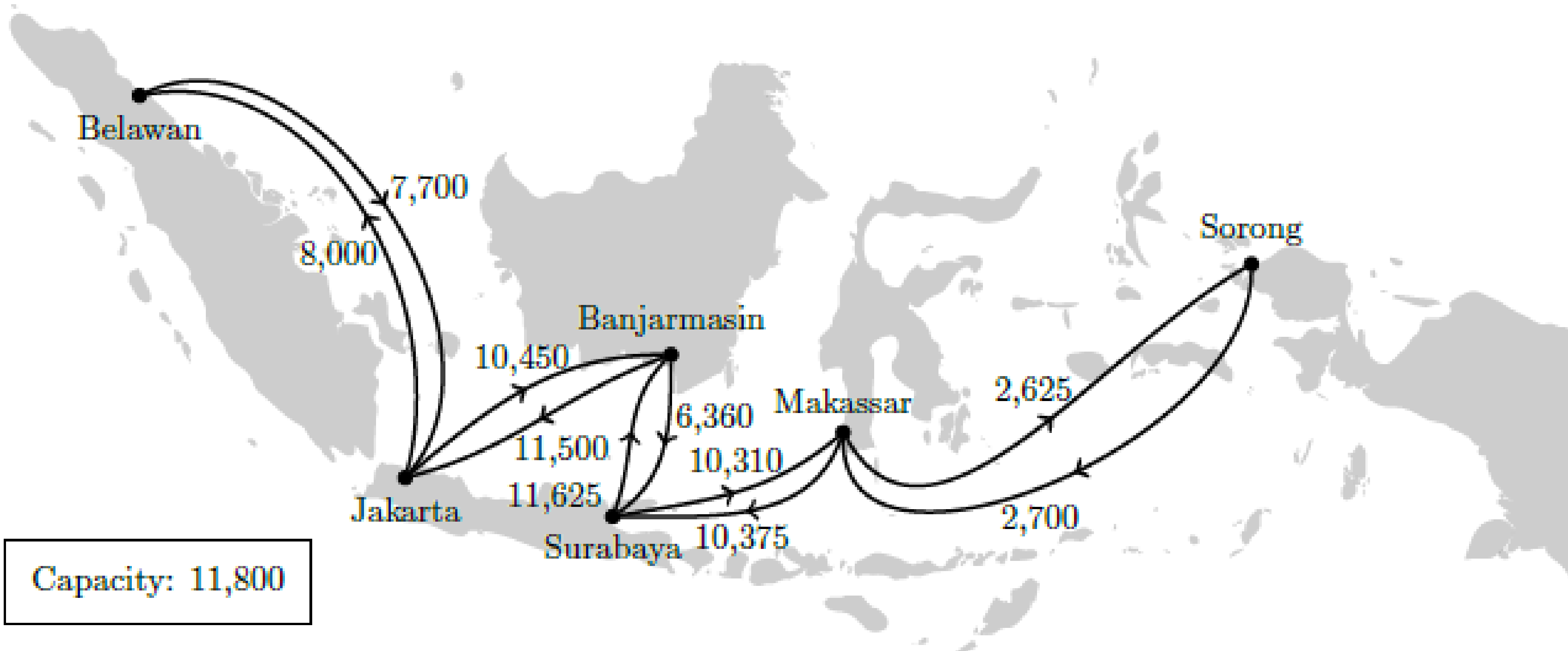


Figure 1.5: Pendulum route network

Route – ship characteristics

Route	Distance (nm)	Duration (weeks)	Frequency (per week)	Required ships	Speed (knots)
F1	2990	2	1	2	11.33*
F2	3632	2	1	2	12.61
F3	1201	1	1	1	12.51
Circular	6476	4	1	4	12.27
Butterfly	6862	4	1	4	13.62

Table 1.4: Route characteristics for the different ships

Route – ship frequencies

Route	Req. cap. (TEU)	Port calls per week					Av. cap. (TEU)	Cost (USD/week)
		Type 1	Type 2	Type 3	Type 4	Type 5		
F1	18,000	0	0	0	4	1	18,800	1,700,643
F2	2,700	0	2	0	0	0	3,200	476,052
F3	15,600	0	1	0	4	0	15,600	703,606
HF-Total								**2,880,300**
Circular	28,485	0	0	0	7	1	29,300	**5,508,321**
Butterfly	18,225	0	0	0	4	1	18,800	**3,935,988**

Table 1.6: Network cost per week when shipping all demand

Optimal fleet size highly dependent on network structure!

Optimality Results

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

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

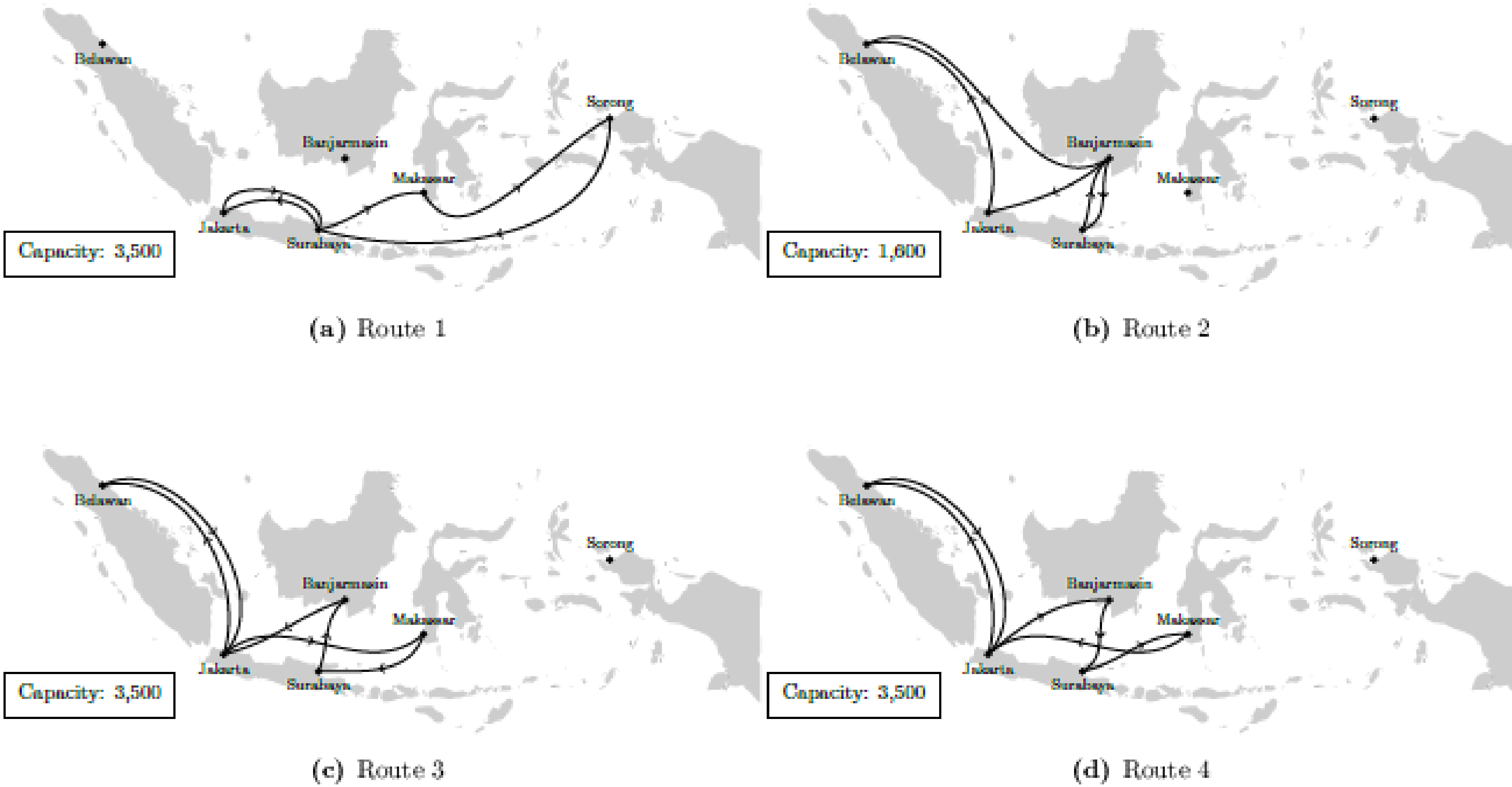


Figure 1.6: Optimal route network

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.