Liner Shipping Single Service Design Problem with Arrival Time Service Levels

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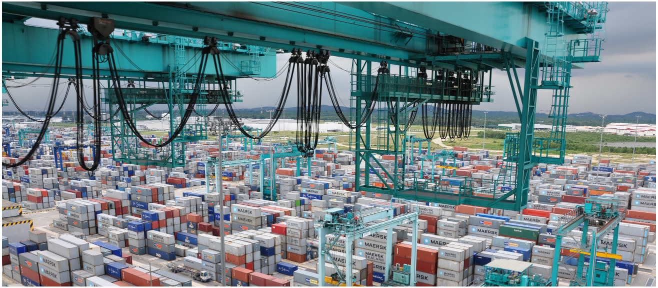
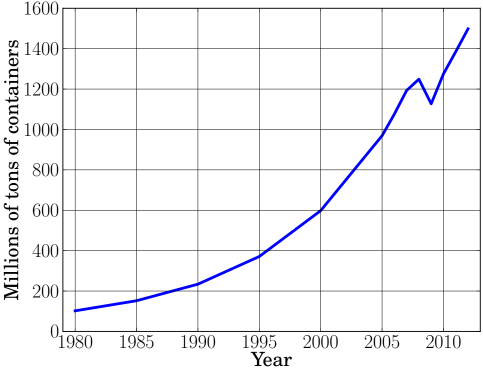
Outline

- Motivation & background
- Data analysis: container ship lateness
- Chance constrained mathematical model for designing services
- Computational results & business insights



Liner Shipping



Data source: UNCTAD Review of Maritime Transport 2016

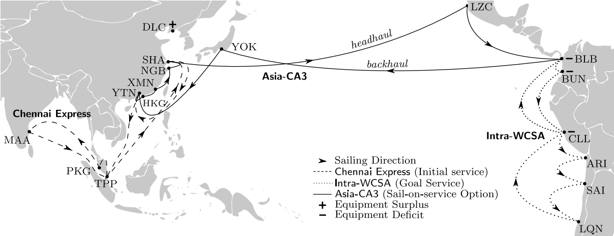
- **Vessels** Over 4900 ships in operation (WSC)
- **Services:** Over 500 services (cyclical routes) available
- **Containers:** Over 180 million twenty-foot equivalent units (TEU) transported in 2016

Liner Shipping: Looking to the Future

“Mærsk Mc Kinney Møller” Walter Rademacher / Wikipedia

> “A major threat to the future of complex liner service networks lies in increased schedule unreliability.”
> – Notteboom and Rodrigue (2008)

Liner Shipping Services

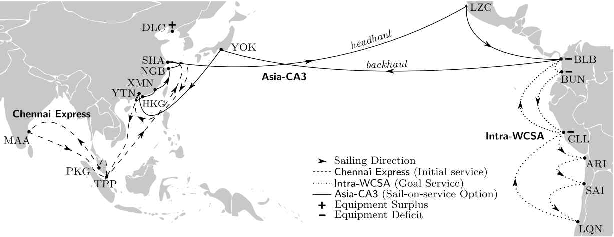


Subset of Maersk Line's network in 2010

Key properties of a liner shipping service:

- **Periodic:** A port is visited on the same day, at the same time, every week (or two weeks, etc.)
- **Cyclical:** A service has no start or end; it loops
- **Enduring:** Most services last months or years

Liner Shipping Services



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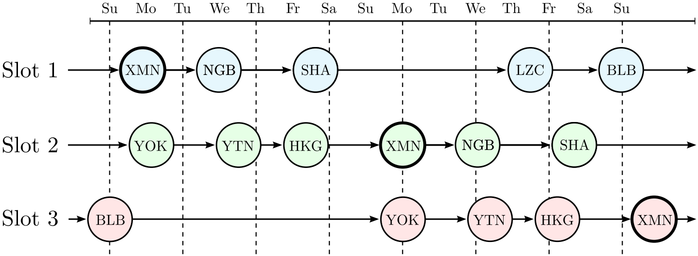


Contribution

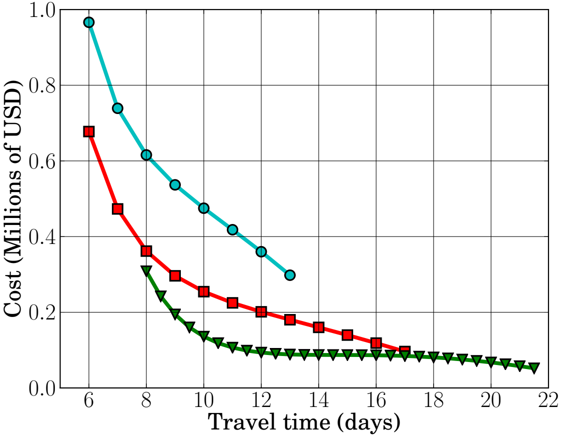
This work provides:

1. A data-driven investigation of liner shipping travel time distributions
2. A mathematical model for designing services with punctuality guarantees
3. A simulation study of the effectiveness of the model

We show that:

1. Punctual services can be designed in reasonable amounts of computation time
2. Guaranteeing punctuality is extremely expensive and in many cases likely not worth it

Slow Steaming



Sailing cost from Boston, USA to Copenhagen, Denmark

Challenge: Incorporate sailing costs and punctuality into the service design process.

Data Analysis: Travel Time Distributions

Data gathering:

- AIS tracking of all vessels on 25 COSCO services in 2014
- Total of 1872 port to port transits around the world
- **Key question:** What distribution best models vessel travel times?

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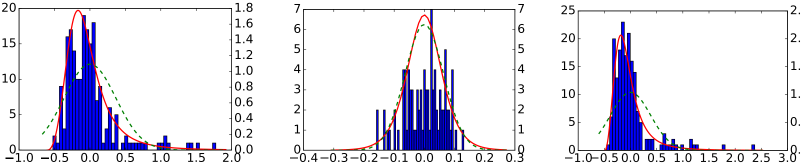
Aggregated, normalized, region-to-region histograms



Intra-Europe | China/Japan to S. Mediterranean | Intra-Western North America

Three-Parameter Log-logistic (LL3P) --- Normal

Designing Liner Shipping Services

Given:

- A set of ports with pre-negotiated time windows
- A set of vessels
- A set of container demands between ports

Goal:

- Plan a route between the ports minimizing:
  1. The sailing cost of the vessels
  2. The total number of vessels
- Optional:
  3. Maximize profit from container demands

Model phases

Phase 1: Design speed

- All ports must be visited exactly once
- Require all demand to be carried within specified path duration
- Only sail at the vessel design speed

Phase 2: Optimized speed

- Phase 1 and...
- Allow vessels to speed up or slow down

Phase 3: Optimized speed with maximum path durations

- Phase 2 and...
- Earn revenue from carrying demand
- Allow rejection of demand

Mathematical Model

Sets/Parameters:

- P – Ports
- A – Arcs
- $(o_k, d_k, a_k) \in K$ – Demands
- t_i^{WS}, t_i^{WE} – Time window
- c^S, c^C – Sailing/charter costs

Decision variables:

- $w_i \in \mathbb{N}$ – Week at port i
- $x_{ij} \in \{0, 1\}$ – 1 iff arc (i, j) used
- $\tau_i^S, \tau_i^E, \tau_i^A \in \mathbb{R}$ – Service start, end, arrival port i
- f_{kij} – Demand k flow on (i, j)

Objective function:

$$\min \; c^C w_{p+1} + \sum_{(i,j)\in A} c_{ij}^S x_{ij}$$

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Objective function:

$$\min \boxed{c^C w_{p+1}} + \boxed{\sum_{(i,j)\in A} c_{ij}^S x_{ij}}$$

- Number of vessels on the service
- Phase 1 fixed sailing cost

Mathematical Model: Constraints

$$\sum_{(i,j)\in A} x_{ij} = 1 \qquad \forall j \in P \text{ except } 1$$

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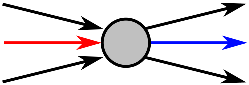

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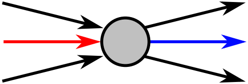
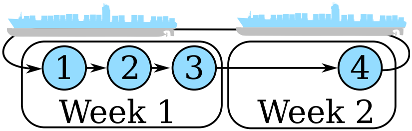


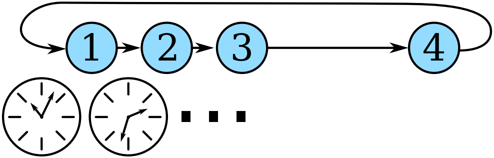
$$\tau_i^S = t_i^{WS} + 168 w_i \qquad \forall i \in P$$

$$\tau_i^E = t_i^{WE} + 168 w_i \qquad \forall i \in P$$



Mathematical Model: Constraints

$$\tau_i^E + t_{ij}^S \leq \tau_j^A + M(1 - x_{ij}) \qquad \forall (i,j) \in A$$



Time feasibility (Also acts as subtour elimination)

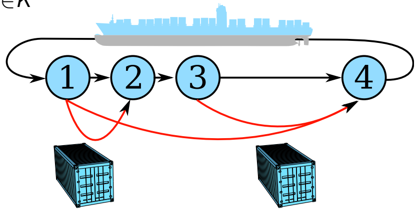
Mathematical Model: Constraints

$$\sum_{j \in P \setminus \{o_k\}} f_{ko_kj} = a_k \qquad \forall k \in K$$

$$\sum_{j \in P \setminus \{d_k\}} f_{kjd_k} = a_k \qquad \forall k \in K$$

$$\sum_{(j,i) \in A'} f_{kji} = \sum_{(i,j) \in A'} f_{kij} \qquad \forall k \in K, i \in P \setminus \{o_k, d_k\}$$

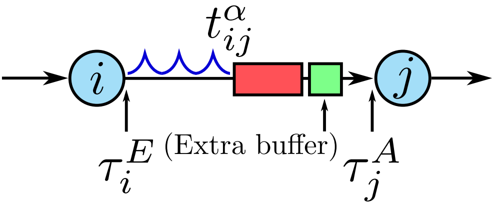
$$\sum_{k \in K} f_{kij} \leq u x_{ij} \qquad \forall (i,j) \in A'$$



Container demands modelled as a multicommodity flow

Modelling Punctuality Guarantees

$$\tau_i^E + t_{ij}^\alpha \leq \tau_j^A + M(1 - x_{ij}) \qquad \forall (i,j) \in A$$



- t_{ij}^α – Amount of buffer necessary to ensure a service level of α for arc (i,j)

Evaluation Procedure

Instances:

- Generated using COSCO service data and the LINERLIB (Brouer et al. 2013)
- 44 instances with between 6 and 13 vessels (COSCO schedule)

Testing procedure:

1. Solve Phase 1/2/3 deterministic and stochastic models
2. Simulate the optimal solution using the LL3P distribution
3. Analyze the expected performance versus the simulated performance

Phases 1/2 Simulation Results

Phase 1:

Distribution	Optimization c^C	c^S	Total	Simulation c^S	|Late|	|Late|/|P|	Faster	Speed
Deterministic	9.7	24.2	61.1	24.9	2.1	27.4	45.4%	16.9
Norm 0.7	11.7	24.5	69.0	17.6	0.7	17.1	11.9%	14.1
Norm 0.9	13.2	24.3	74.3	15.7	0.4	10.1	6.4%	13.4
LL3P 0.7	11.3	24.3	67.1	18.5	0.8	16.6	16.5%	14.6
LL3P 0.9	13.9	24.3	76.9	15.1	0.3	2.8	4.5%	13.2
LL3P 0.95	17.6	24.6	91.3	14.0	0.0	0.1	1.6%	12.7

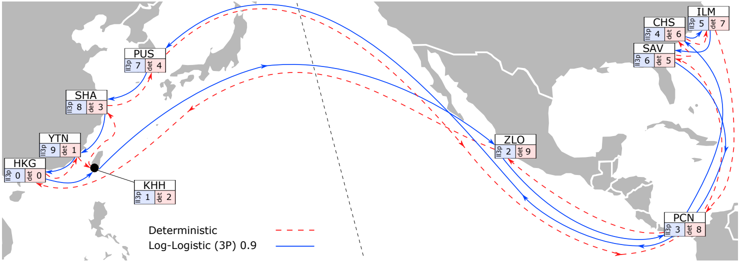
Phase 2:

Distribution	Optimization c^C	c^S	Total	Speed	Simulation c^S	|Late|	|Late|/|P|	Faster	Speed
Deterministic	9.9	16.5	54.1	14.01	19.6	1.8	22.0	29.5%	15.1
Norm 0.7	11.8	14.2	58.8	12.92	15.2	0.5	13.4	9.4%	13.3
Norm 0.9	13.2	13.3	63.3	12.56	14.0	0.3	7.1	4.7%	12.8
LL3P 0.7	11.2	15.0	57.6	13.29	16.4	0.6	13.0	12.7%	13.8
LL3P 0.9	13.8	13.2	65.4	12.52	13.5	0.1	1.9	3.0%	12.6
LL3P 0.95	17.3	13.3	78.6	12.48	13.3	0.0	0.1	1.2%	12.5

Phase 3: Demand Carried (Det/LL3P)

Service	Cargo carried (%)				Transit inc. (%)		
	Det	0.7	0.9	0.95	0.7	0.9	0.95
abx	93	86	70	69	11	956	1446
aesa	78	32	22	20	44	102	163
awe1	39	15	14	14	42	107	149
awe2	15	15	15	13	12	-1	35
awe3	19	11	6	6	67	125	192
awe4	31	11	8	8	63	173	278
awe8	11	8	8	2	252	307	422
cen	79	16	7	7	68	90	144
ces	90	47	45	43	161	201	247
ese	70	15	14	10	33	87	98

Sample solutions



Phase 1 optimization of the AWE3 service

Conclusion

- Services can be designed with puncutality guarantees at low computational cost
- However, the operational costs may be high
- Acceptance from shippers is necessary to implement such services

Literature Overview

Article	Routing	Distribution	Speed opt.	Method
Wang and Meng (2012)	✗	Unif. & Norm.	✓(NL)	NL stoch. prog.
Wang and Meng (2012)	✗	Any Truncated	✓(NL)	NL stoch. prog.
Qi and Song (2012)	✗	Unif./Norm.	✓(NL)	Sim. stoch. approx.
Song and Dong (2013)	✓	✗	✓(NL)	Heuristic Decomp.
Plum et al. (2014)	✓	✗	✗	Branch-Cut-and-Price
Lee et al. (2015)	✗	Normal/Any	✓(NL)	Markov chains
Song et al. (2015)	✗	Trunc. Norm.	✓(NL)	NSGA-II
Reinhardt et al. (2016)	✗	✗	✓(SAX)	MILP
Wang and Wang (2016)	✗	✗	✓(NL)	P time alg.
This paper	✓	log-logistic 3P	✓(SAX)	MILP

NL = Non-linear; SAX = Secant approximation