Global planning in a multi-terminal and multi-modal maritime container port

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Outline

1. Context
   - Inter-port competition
   - Multi-terminal systems
   - Existing studies
2. Contributions
   - Model and formulation
   - Solving methodology
   - Numerical experiments
3. Conclusion and perspectives

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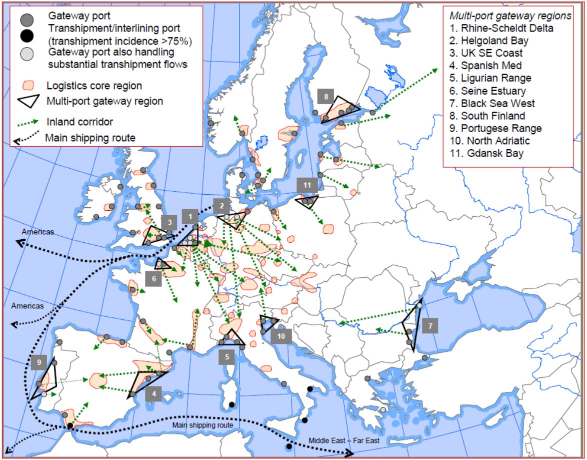
Inter-port competition



European container port system, Notteboom 2010

Two key competitive factors:

- Vessel turnaround time[a]
- Quality of road, rail, river connections[b]

[a] Tongzon and Heng 2005, TR part A.
[b] Wiegmans, Hoest, and Notteboom 2008.

Recent infrastructure investment, Le Havre

Port 2000

Recent infrastructure investment, Le Havre

Rail and river terminal

Multi-terminal systems

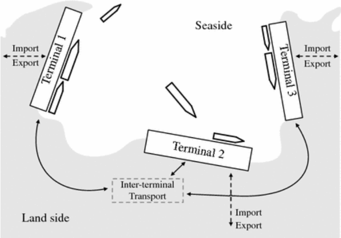
Evolution of container transport

- Surge of world traffic:
  from 84.6 millions TEUs in 1990 to 602 millions in 2012
- Expected modal shift from road to rail and river
- More transshipments (hub-and-spoke networks)

Multi-terminal systems

- Split of container traffic among terminals within the port
- Inter-terminal transport of containers
  - Coordination of operations between terminals

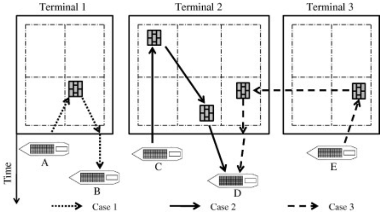
Existing multi-terminal studies



"Strategic allocation of cyclically calling vessels for multi-terminal container operators"[a]

- Allocation of liner services to terminals
- Allocation of berthing and departure times to each service
- **Objective**: balance quay crane workload, minimize inter-terminal transport

[a] Hendriks, Armbruster, Laumanns, Lefeber, and Udding 2012.



"Terminal and yard allocation problem for a container transshipment hub with multiple terminals"[a]

- Terminal and storage allocation of containers
- **Objective**: minimize intra-terminal and inter-terminal handling costs

[a] Lee, Jin, and Chen 2012.

Outline

General characteristics of the model

- **Objective** : minimize weighted tardiness of ships and trains
- Global model
  - Providing baselines for planning at an operational level
  - Grouping of trucks
  - Grouping of containers
  - Representation of inter-terminal container transport as a capacitated flow
- Multi-periodic
  - Equal-length periods
  - Target horizon: 5 days
- Constraints by vehicle type: ship, train, truck
- Constraints on container handling

Vehicles

Ship, train

- Ready time
- Due date
- Cost of tardiness
- Deadline

Ship

- Length
- Maximum number of cranes

Truck

- *Appointment system*

Container batch

Definition

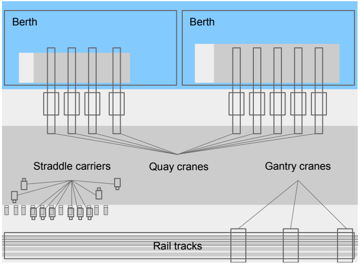
- Representation of containers in the model
- Set of containers transshipped between two vehicles

Constraints

- Unloaded (resp. Loaded) in one terminal
- At most one inter-terminal transport

Terminal resources

Figure: Handling zones and groups of cranes



- Storage capacity, in Twenty-foot Equivalent Units
- Container-processing capacity per period
- Inter-terminal transport, between each pair of terminals:
  - Transport capacity, in containers per period
  - Transport duration

Time-indexed formulation

- Constraints on ships on the right
- Many more constraints ...

$$\sum_{\substack{v\in \mathrm{V}_\mathrm{A}:\\ z\in \mathrm{Z}_v, t\in \mathrm{T}_v}} (\kappa_v \cdot p_{vz}^t) \le \kappa_z \quad \forall z\in \mathrm{Z}_\mathrm{A}, \forall t\in \mathrm{T}$$

$$\sum_{\substack{v\in \mathrm{V}_\mathrm{A}:\\ z\in \mathrm{Z}_v, t\in \mathrm{T}_v}} p_{vz}^t \le 2 \quad \forall z\in \mathrm{Z}_\mathrm{A}, \forall t\in \mathrm{T}$$

$$\sum_{\substack{v\in \mathrm{V}_\mathrm{A}:\\ z\in \mathrm{Z}_v, t\in \mathrm{T}_v}} \sum_{n=1}^{\eta_v^z} (n\cdot h_{vz}^{nt}) \le \eta_z \quad \forall z\in \mathrm{Z}_\mathrm{A}, \forall t\in \mathrm{T}$$

$$\sum_{\substack{z\in \mathrm{Z}_\mathrm{A}:\\ \gamma_z = g}} \sum_{\substack{v\in \mathrm{V}_\mathrm{A}:\\ z\in \mathrm{Z}_v, t\in \mathrm{T}_v}} \sum_{n=1}^{\eta_v^z} (n\cdot h_{vz}^{nt}) \le \eta_g \quad \forall g\in \mathrm{G}_\mathrm{A}, \forall t\in \mathrm{T}$$

$$\sum_{\substack{b\in \mathrm{BU}_v:\\ t\in \mathrm{TU}_b}} u_{bc}^t + \sum_{b\in \mathrm{BL}_v} l_{bc}^t \le \sum_{\substack{z\in \mathrm{Z}_v:\\ c=\zeta_z}} \sum_{n=1}^{\eta_v^z} (\rho_{\gamma_z}^n \cdot h_{vz}^{nt}) \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall c\in \mathrm{C}_v, \forall t\in \mathrm{T}_v$$

$$\sum_{z\in \mathrm{Z}_v} p_{vz}^t \le 1 \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall t\in \mathrm{T}_v$$

$$m_v \ge (t-d_v)\cdot \left(\sum_{z\in \mathrm{Z}_v} p_{vz}^t\right) \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall t\in [\![d_v+1, \overline{d}_v]\!]$$

$$-\sum_{b\in \mathrm{BU}_v} \sum_{c\in \mathrm{C}_v} \sum_{\substack{t'\in \mathrm{T}_v:\\ t'\le t}} \left(\frac{\tilde{\eta}_b}{\eta_b}\cdot u_{bc}^{t'}\right) + \sum_{b\in \mathrm{BL}_v} \sum_{c\in \mathrm{C}_v} \sum_{\substack{t'\in \mathrm{T}_v:\\ t'\le t}} \left(\frac{\tilde{\eta}_b}{\eta_b}\cdot l_{bc}^{t'}\right) \le \delta_v \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall t\in \mathrm{T}_v$$

$$\sum_{z\in \mathrm{Z}_v} \sum_{t\in \mathrm{T}_v} \underline{h}_{vz}^t = 1 \quad \forall v\in (\mathrm{V}_\mathrm{A}\cap \tilde{\mathrm{V}})$$

$$\overline{h}_{vz}^t + \sum_{z'\in \mathrm{Z}_v} \sum_{t'=t+1}^{\min\{t+\tau_z^{z'}, \overline{d}_v\}} \underline{h}_{v,z'}^{t'} \le 1 \quad \forall v\in \left(\mathrm{V}_\mathrm{A}\setminus \tilde{\mathrm{V}}\right), \forall z\in \mathrm{Z}_v, \forall t\in \mathrm{T}_v$$

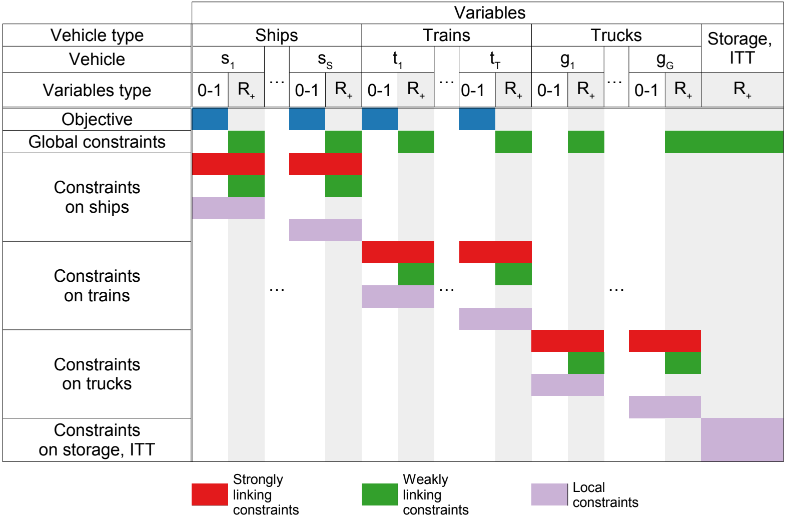
$$\underline{h}_{vz}^{r_v} - p_{vz}^{r_v} = 0 \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall z\in \mathrm{Z}_v$$

$$\underline{h}_{vz}^{t+1} + p_{vz}^t - p_{vz}^{t+1} - \overline{h}_{vz}^t = 0 \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall z\in \mathrm{Z}_v, \forall t\in \left(\mathrm{T}_v\setminus \{\overline{d}_v\}\right)$$

$$p_{vz}^{\overline{d}_v} - \overline{h}_{vz}^{\overline{d}_v} = 0 \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall z\in \mathrm{Z}_v$$

$$p_{vz}^t = \sum_{n=0}^{\eta_v^z} h_{vz}^{nt} \quad \forall v\in \mathrm{V}_\mathrm{A}, \forall z\in \mathrm{Z}_v, \forall t\in \mathrm{T}_v$$

Structural representation of the problem



Overview of the solving methodology

Limitations of exact methods

- State-of-the-art mixed-integer linear program solver
  - Solving of realistic small to mid-sized instances
- Extended formulation and branch-and-price
  - Solving of realistic small instances

Mixed-integer programming based heuristic approach

- Based on the structural decomposition of the formulation
  - Relax-and-fix
  - Restrict-and-fix

Relax-and-fix[1]

Definition

- Heuristic for mixed-integer programs
- Requires an ordered partition of the set of **integer** variables
- At each iteration:
  - Relaxation of integrality constraints for all but the current subset
  - Solving of the resulting sub-problem
  - Fixing of the integer variables at their current values

- Partition of binary variables by vehicle type
- Possible subpartition according to how time windows intersect
- First ships, then trains, then trucks

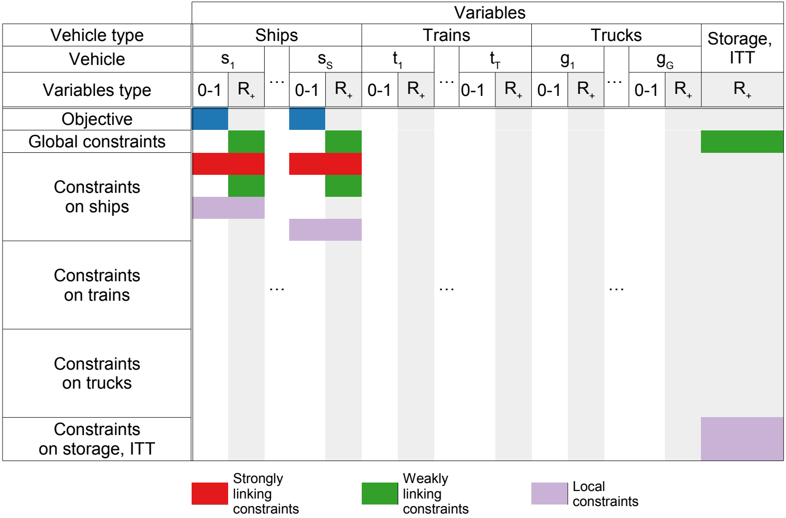
[1] Described by Wolsey 1998.

Restrict-and-fix

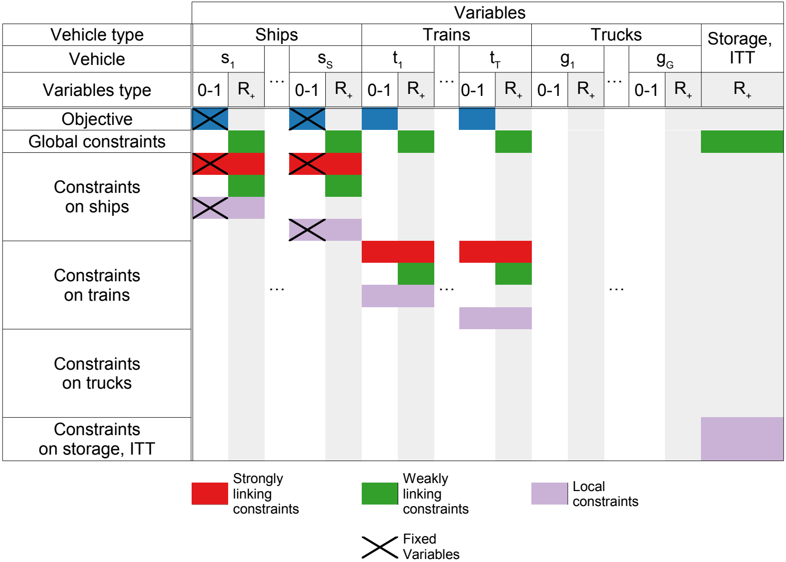
Definition

- Requires an ordered partition of the set of variables
- At each iteration:
  - Additional subset of integer and continuous variables
  - Fixing of its integer variables by solving a *subproblem*
  - The subproblem includes:
    - Current and all previous subsets of variables
    - Constraints containing only theses variables (other linear constraints are relaxed)
- Continuous variables are fixed at the last iteration
- Constraints may be added to a subproblem to increase feasibility

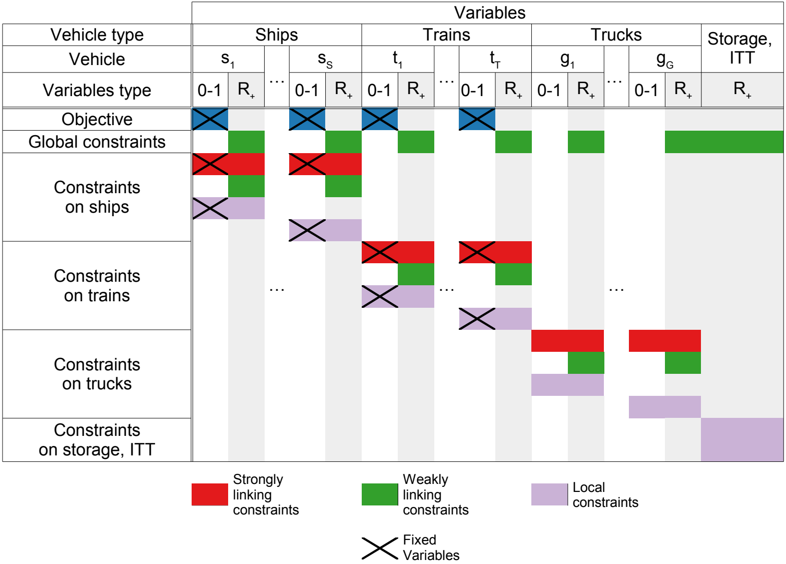
Restrict-and-fix - subproblem 1



Restrict-and-fix - subproblem 2



Restrict-and-fix - last subproblem



General characteristics of the instances

- Due date = ready time (minimize weighted turnaround time)
- Period length of 2 hours
- Arrivals of vehicles over 5 or 7 days
- Four terminal configurations:
  - 1, 2 or 3 compact terminal(s)
  - 3 terminals dedicated to sea and road
    plus 1 terminal dedicated to inland waterway and rail.
- 3 annual levels of traffic:
  - 1 millions of TEUs[2]
  - 1.5 millions of TEUs
  - Le Havre: 2.5 millions of TEUs

[2] Twenty-foot Equivalent Units

Contents of the instances

Table: Vehicles and container batches by level of traffic

Traffic [a]	Horizon	Vehicle type			Batches [b]
		Ship	Train	Truck	
1	5 days	4 mother vessels 10 feeder vessels 29 inland-waterway barges	17	8 groups	183.4
1	7 days	5 mother vessels 14 feeder vessels 40 inland-waterway barges	24	10 groups	298.6
1.5	5 days	6 mother vessels 15 feeder vessels 43 inland-waterway barges	26	12 groups	286.7
2.5	5 days	15 mother vessels 24 feeder vessels 71 inland-waterway barges	42	30 groups	574

[a] annual millions of TEUs

[b] average number

Numerical results

Comparative results

- Methods:
  - Direct solving by a solver
  - Relax-and-fix:
    between 5 and 7 subproblems for ships,
    1 subproblem for trains,
    1 subproblem for trucks
  - Restrict-and-fix: subproblem for ships solved by relax-and-fix
- Solver: IBM ILOG CPLEX 12.6
- Time limit of 7200 s.
- CPU at 3 Ghz, 8 Gb of RAM

Numerical results: 1 terminal, 1 annual m^n of TEUs

Instance	CPLEX				Relax-and-fix		Restrict-and-fix	
	time	LR	LB	value	time	value	time	value
I_1_1_5 #1	54.3	74927.3	82224	82224	21.8	82224	18.1	82224
I_1_1_5 #2	82.3	75887.1	84046	84046	13.5	84046	9.1	84046
I_1_1_5 #3	93.2	77974.9	88312	88312	67.7	88312	41.1	88312
I_1_1_5 #4	111.8	77273.3	85724	85724	43.7	85724	18.2	85724
I_1_1_5 #5	89.9	77683.4	85556	85556	24.5	85556	21.2	85556
I_1_1_7 #1	7200	111536.7	123641	123708	96.2	123708	51.3	123708
I_1_1_7 #2	7200	113195.9	125753	127656	151.1	127656	87.2	127656
I_1_1_7 #3	2269.9	115650.8	128966	128966	83.1	128966	65.3	128966
I_1_1_7 #4	499.1	114252.7	129310	129310	70.7	129310	57.3	129310
I_1_1_7 #5	783.8	118329.8	133408	133408	140.1	133408	121.2	133408

Numerical results: 2 terminals, 1.5 annual m^{ns} of TEUs

- Both heuristics provide solutions to the 25 instances
  - 133276,8 on average for relax-and-fix
  - 133303,7 for restrict-and-fix
  - Average relative gap value with the lower bound $< 3\%$
- CPLEX
  - solves to optimality 4 instances,
  - provides feasible solutions to 4 others.
- Average running times:
  - 6302 s. for CPLEX
  - 988 s. for relax-and-fix
  - 801 s. for restrict-and-fix

Numerical results: 3 terminals, 2.5 annual m^{ns} of TEUs

- Only restrict-and-fix provides solution to the 25 instances
  - Average relative gap value with the lower bound $< 11\%$
- Relax-and-fix
  - provides solutions to 20 instances.
- CPLEX
  - provides feasible solutions to 3 instances.

Decrease of weighted turnaround time

2 terminals, 1.5 annual m^{ns} of TEUs

Allowing 5% or 10% of the containers to use ITT[a]:
4% decrease of the weighted turnaround time.

[a] Inter-Terminal Transport

3 terminals, 2.5 annual m^{ns} of TEUs

- Allowing 5% of the containers to use ITT:
  5% decrease of the weighted turnaround time.
- Allowing 10%:
  6% decrease.

In both cases, increasing the capacity of ITT from 30 containers per hour between any couple of terminals to 60 doesn't notably further reduces weighted turnaround time.

Numerical results: 4 terminal, 2.5 annual m^{ns} of TEUs

Instance	CPLEX				Relax-and-fix		Restrict-and-fix	
	time	LR	LB	value	time	value	time	value
I_4_2.5_5 #1	7200	188722	204218	-	4870.7	221642	153.1	217046
I_4_2.5_5 #2		187303.6	205309		3901.9	218240	517.3	214936
I_4_2.5_5 #3		198707.4	214847		1113.4	230456	882.1	227950
I_4_2.5_5 #4		200690.6	217192		4837.4	232036	791.1	225922
I_4_2.5_5 #5		199070.4	220396		1540.8	231752	721.2	228510

Outline

Conclusion

- First global model for a multi-terminal multi-modal maritime port
- **Objective**: minimize weighted tardiness
- Solving methodology
  - Direct solving by a state-of-the-art solver
  - Relax-and-fix
  - New heuristic: restrict-and-fix
- Numerical results
  - Close to optimal solution to all instances by restrict-and-fix
  - Evaluation of the decrease of weighted turnaround time that inter-terminal container transport can achieve

Perspectives

- Application of restrict-and-fix to other problems
  - Research and study of adequate structures
- Robust or stochastic optimization
  - To deal with uncertainties, for example on vessel arrivals