Optimization in container terminals

Hierarchical vs integrated solution approaches

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Outline

- Container terminals
- Berth Allocation Problem (BAP)
- Quay Cranes Assignment Problem (QCAP)
- Hierarchical vs Integrated solution approaches
- Computational results

Motivation

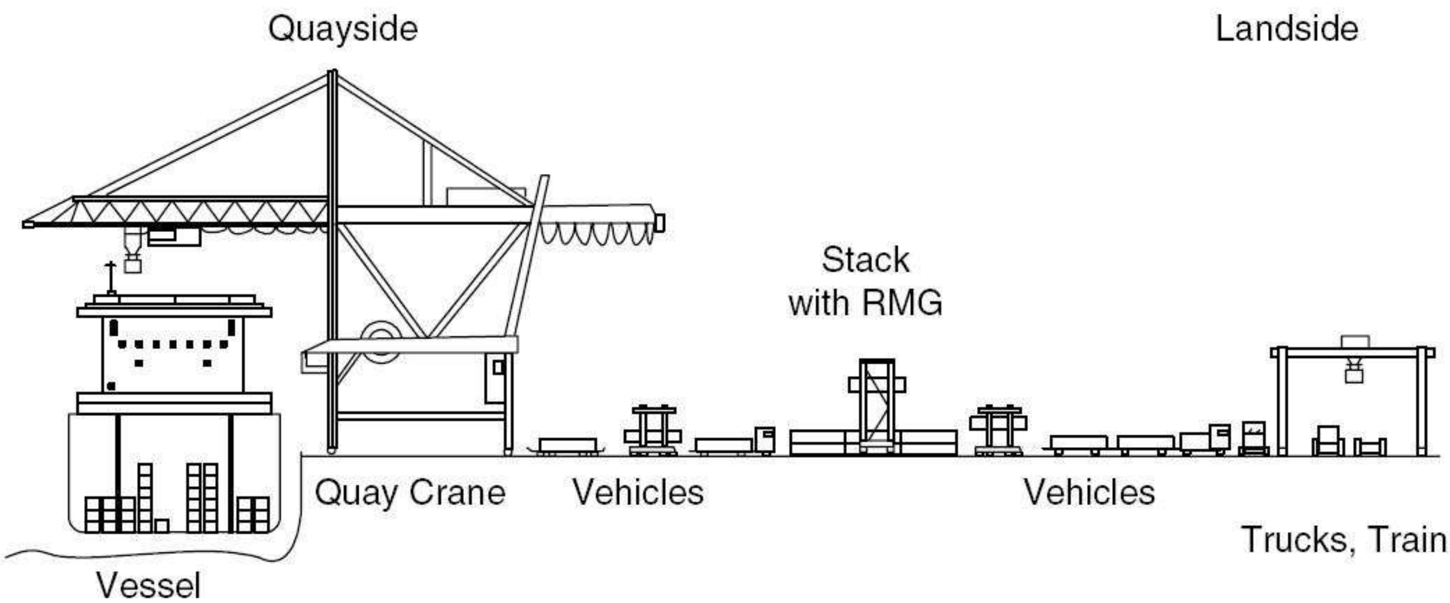
Worldwide		2004	2006		2008	
1	Singapore	21’329	24’792	(+16%)	29’918	(+21%)
2	Shanghai	14’557	21’710	(+49%)	27’980	(+29%)
3	Hong Kong	21’984	23’539	(+07%)	24’248	(+03%)

Europe		2004	2006		2008	
1	Rotterdam	8’291	9’655	(+17%)	10’784	(+12%)
2	Hamburg	7’003	8’862	(+27%)	9’737	(+10%)
3	Antwerp	6’064	7’019	(+16%)	8’663	(+23%)

Table 1: Container traffic (in thousands TEUs).

Container terminals

Container terminals



Scheme of a container terminal system (Steenken et al., 2004).

The Berth Allocation Problem (BAP)

Input

- a set of vessels, a set of berths, a time horizon;
- *an expected handling time for every vessel;*
- a time window on the vessel's handling time;

Output

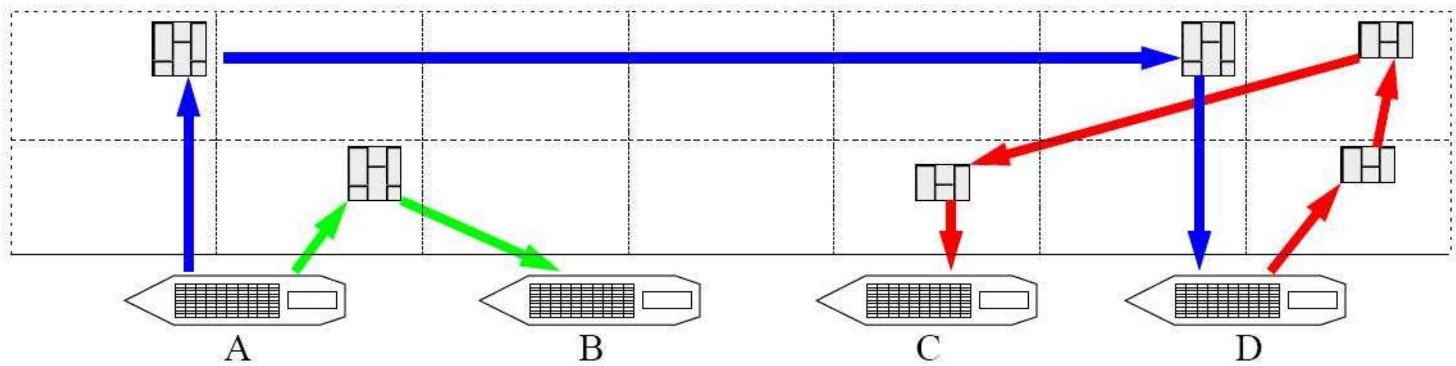
- an assignment of vessels to berths;
- a scheduling of vessels over time;

Objectives

- minimize the total delay;
- minimize the completion time;
- *minimize the housekeeping costs.*

Yard Housekeeping Costs

In the context of a *transshipment container terminal*, we take into account the cost generated by the exchange of containers between ships in terms of traveled distance.



Piecewise linear function depending on the distance and on the type of carrier used:

- < 600m : no housekeeping, straddle carriers
- 600 - 1100 m : housekeeping, straddle carriers
- > 1100 m : housekeeping, multi-trailer

The Quay Crane Assignment Problem (QCAP)

Input

- *a berth allocation plan*;
- the workload of every vessel;
- the maximum number of available QCs;

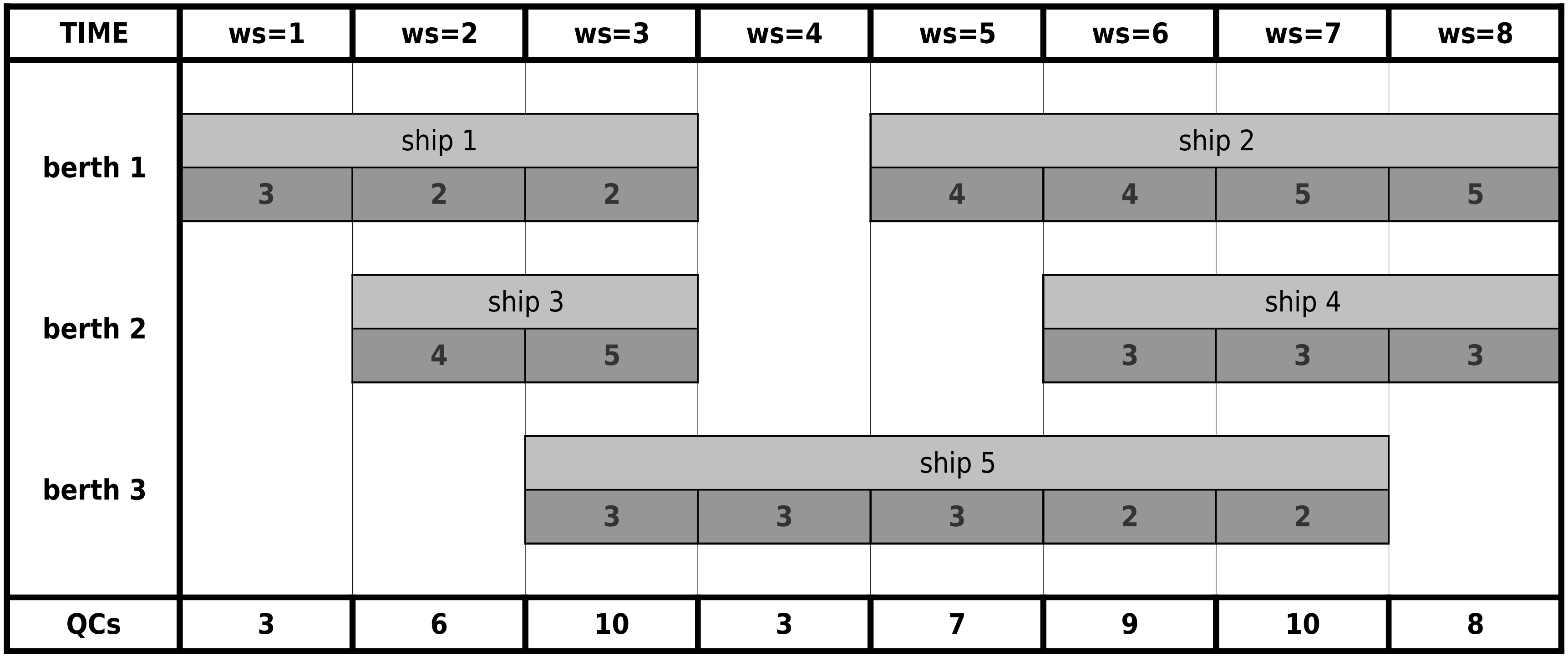
Output

- a quay crane assignment to vessels;

Objectives

- minimize the turn-around time;
- minimize the completion time;
- *maximize the monetary value associated to qc profiles.*

Berth allocation plan with QC assignment



BAP and QCAP are strictly interdependent:

- the expected handling time depends on the number of assigned QCs;
- given a berth allocation plan, the QC capacity must be satisfied.

The Tactical Berth Allocation Problem (TBAP)

Integrated optimization of BAP and QCAP we solve the two problems simultaneously.

Tactical decision level we analyze the problem from the terminal point of view, in order to provide decision support in the context of the negotiation between the terminal and shipping lines.

Quay-crane profiles we introduce the concept of quay crane profile, i.e. the number of cranes assigned to a vessel over time. QC profiles can vary in length (number of shifts) and in size (number of QCs).

Handling time the handling time becomes a decision variable, that depends on the assigned quay crane profile.

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Hierarchical solution approach

The hierarchical approach consists of the following steps:

1. determine the expected handling time for every ship;
2. BAP: solve the berth allocation problem, taking into account ships' time windows and berths' availability;
3. QCAP: assign a qc profile to every ship, taking into account the qc capacity constraint and the given berth allocation plan.

Methodology:

- the BAP is solved exactly by a branch-and-price algorithm;
- the QCAP is solved by a general-purpose MIP solver.

Handling time estimation

We consider 2 scenarios for the handling time:

- scenario A : longest feasible profile for every ship;
- scenario B : max-value profile for mother vessels, longest feasible profile for feeders.

Scenario A represents a conservative approach (worst case scenario).

Scenario B is more realistic, although it may lead to infeasibility of QCAP.

Integrated solution approach

- MIQP and MILP formulations for TBAP.
- Tabu search heuristic for TBAP.
- Dantzig-Wolfe reformulation.
- Column generation: master problem and pricing subproblem.
- Exact branch-and-price algorithm.

Results: 10 vessels, 1 week ('easy')

	BAP+QCAP Scen.A			BAP+QCAP Scen.B			Integrated TBAP				
$inst$	obj	K	$t(s)$	obj	K	$t(s)$	obj	K	$t(s)$	$\%(A)$	$\%(B)$
H1_10	**787167**	2	15	**789478**	2	26	**790735**	2	114	0.45%	0.16%
H1_20	**787117**	2	16	**789754**	2	16	**791011**	2	995	0.49%	0.16%
H1_30	**787151**	2	16	**789788**	2	16	**791045**	2	557	0.49%	0.16%
H2_10	**730702**	2	3	**733276**	2	2	**733276**	2	12	0.35%	0.00%
H2_20	**730418**	2	6	**732659**	2	6	**735646**	2	29	0.72%	0.41%
H2_30	**730454**	2	4	**732695**	2	6	**735682**	2	25	0.72%	0.41%
L1_10	**513661**	2	85	**515017**	2	308	**515902**	2	4054	0.44%	0.17%
L1_20	**513696**	2	21	**515052**	2	171	**518049**	2	761	0.85%	0.58%
L1_30	**513731**	2	21	**515087**	2	173	**518084**	2	470	0.85%	0.58%
L2_10	**559683**	2	30	**561705**	2	24	**564831**	2	4697	0.92%	0.56%
L2_20	**559719**	2	14	**561741**	2	26	**564867**	2	1573	0.92%	0.56%
L2_30	**559755**	2	14	**561777**	2	27	**564903**	2	2680	0.92%	0.56%

Results: 10 vessels, 4 days ('congested')

	BAP+QCAP Scen.A			BAP+QCAP Scen.B			Integrated TBAP				
$inst$	obj	K	$t(s)$	obj	K	$t(s)$	obj	K	$t(s)$	$\%(A)$	$\%(B)$
H1_10	x			x			**777398**	3	59	$+\infty$	$+\infty$
H1_20	**776331**	3	11	x			**779674**	3	150	0.43%	$+\infty$
H1_30	**776365**	3	12	x			**782300**	3	93	0.76%	$+\infty$
H2_10	x			x			**722431**	3	45	$+\infty$	$+\infty$
H2_20	**719927**	3	7	**722674**	3	8	**724345**	3	55	0.61%	0.23%
H2_30	**719998**	3	5	**722674**	3	8	**725585**	3	53	0.78%	0.40%
L1_10	**507528**	3	5	x			**512533**	2	17	0.99%	$+\infty$
L1_20	**507365**	3	4	**508505**	3	8	**512533**	2	107	1.02%	0.79%
L1_30	**507400**	3	4	**508540**	3	8	**512991**	2	1725	1.10%	0.88%
L2_10	**553971**	3	6	**556179**	3	11	**558750**	2	69	0.86%	0.46%
L2_20	**554380**	3	6	**556272**	3	9	**558786**	2	197	0.79%	0.45%
L2_30	**554380**	3	6	**556280**	3	10	**558822**	2	86	0.80%	0.46%

Conclusions

- The hierarchical approach provides good and fast solutions on ’easy’ instances.
- The integrated approach performs significantly better for ’congested’ instances.
- The increased complexity of the simultaneous optimization allows for significant savings, both in terms of feasibility and utilization of resources.

Thanks for your attention!

The Tactical Berth Allocation Problem (TBAP)

Decision variables

- berth assignment : $y_i^k \in \{0,1\}$;
- profiles' assignment : $\lambda_i^p \in \{0,1\}$;
- ship scheduling : $x_{ij}^k \in \{0,1\}$, $T_i^k \geq 0$.

Objective function : maximize total value of QC profile assignments & minimize the housekeeping yard cost of transshipment flows:

$$\max \sum_{i \in N} \sum_{p \in P_i} v_i^p \lambda_i^p - \frac{1}{2} \sum_{i \in N} \sum_{k \in M} y_i^k \sum_{j \in N} \sum_{w \in M} f_{ij} d_{kw} y_j^w \qquad (1)$$

The Tactical Berth Allocation Problem (TBAP)

Berth assignment

$$\sum_{k \in M} y_i^k = 1 \qquad \forall i \in N, \tag{2}$$

Flow constraints

$$\sum_{j \in N \cup \{d(k)\}} x^k_{o(k),j} = 1 \qquad \forall k \in M, \tag{3}$$

$$\sum_{i \in N \cup \{o(k)\}} x^k_{i,d(k)} = 1 \qquad \forall k \in M, \tag{4}$$

$$\sum_{j \in N \cup \{d(k)\}} x^k_{ij} - \sum_{j \in N \cup \{o(k)\}} x^k_{ji} = 0 \qquad \forall k \in M, \forall i \in N, \tag{5}$$

$$\sum_{j \in N \cup \{d(k)\}} x^k_{ij} = y^k_i \qquad \forall k \in M, \forall i \in N, \tag{6}$$

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The Tactical Berth Allocation Problem (TBAP)

Time computation

$$T_i^k + \sum_{p \in P_i} t_i^p \lambda_i^p - T_j^k \leq (1 - x_{ij}^k)M \qquad \forall k \in M, \forall i \in N, \forall j \in N \cup d(k) \quad (7)$$

$$T_{o(k)}^k - T_j^k \leq (1 - x_{o(k),j}^k)M \qquad \forall k \in M, \forall j \in N, \quad (8)$$

Ship and Berth time windows

$$a_i y_i^k \leq T_i^k \qquad \forall k \in M, \forall i \in N, \quad (9)$$

$$T_i^k \leq b_i y_i^k \qquad \forall k \in M, \forall i \in N, \quad (10)$$

$$a^k \leq T_{o(k)}^k \qquad \forall k \in M, \quad (11)$$

$$T_{d(k)}^k \leq b^k \qquad \forall k \in M, \quad (12)$$

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The Tactical Berth Allocation Problem (TBAP)

QC profile assignment & linking constraints

$$\sum_{p \in P_i} \lambda_i^p = 1 \qquad \forall i \in N, \tag{13}$$

$$\sum_{h \in H^s} \gamma_i^h = \sum_{p \in P_i^s} \lambda_i^p \qquad \forall i \in N, \forall s \in S, \tag{14}$$

$$\sum_{k \in M} T_i^k - b^h \leq (1 - \gamma_i^h) M \qquad \forall h \in H, \forall i \in N, \tag{15}$$

$$a^h - \sum_{k \in M} T_i^k \leq (1 - \gamma_i^h) M \qquad \forall h \in H, \forall i \in N, \tag{16}$$

$$\rho_i^{ph} \geq \lambda_i^p + \gamma_i^h - 1 \qquad \forall h \in H, \forall i \in N, \forall p \in P_i, \tag{17}$$

QC total capacity

$$\sum_{i \in N} \sum_{p \in P_i} \sum_{u=max\{h - t_i^p + 1;1\}}^{h} \rho_i^{pu} q_i^{p(h-u+1)} \leq Q^h \qquad \forall h \in H^{\bar{s}} \tag{18}$$

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TBAP linearization

Additional decision variable

$z_{ij}^{kw} \in \{0,1\}\ \forall i,j \in N,\ \forall k,w \in M$, set to 1 if $y_i^k = y_j^w = 1$ and 0 otherwise.

Linearized objective function

$$\max \quad \sum_{i\in N}\sum_{p\in P_i} v_i^p \lambda_i^p - \frac{1}{2}\sum_{i\in N}\sum_{j\in N}\sum_{k\in M}\sum_{w\in M} f_{ij} d_{kw} z_{ij}^{kw} \tag{19}$$

Additional constraints

$$\sum_{k\in K}\sum_{w\in K} z_{ij}^{kw} = g_{ij} \qquad \forall i,j \in N, \tag{20}$$

$$z_{ij}^{kw} \le y_i^k \qquad \forall i,j \in N, \forall k,w \in M, \tag{21}$$

$$z_{ij}^{kw} \le y_j^w \qquad \forall i,j \in N, \forall k,w \in M. \tag{22}$$

Master problem

Objective function

$$\min \frac{1}{2} \sum_{i \in N} \sum_{j \in N} \sum_{k \in M} \sum_{w \in M} z_{ij}^{kw} f_{ij} d_{kw} - \sum_{k \in M} \sum_{r \in \Omega^k} v_r \lambda_r \tag{23}$$

Serve every ship

$$\text{s.t.} \sum_{k \in M} \sum_{r \in \Omega^k} \alpha_r^i \lambda_r = 1 \quad \forall i \in N, \tag{24}$$

QC total capacity

$$\sum_{k \in M} \sum_{r \in \Omega^k} q_r^h \lambda_r \leq Q^h \quad \forall h \in H, \tag{25}$$

Convexity constraints

$$\sum_{r \in \Omega^k} \lambda_r \leq 1 \quad \forall k \in M, \tag{26}$$

References

Steenken, D., Voss, S. and Stahlbock, R. (2004). Container terminal operation and operations research - a classification and literature review, *OR Spectrum* **26**: 3–49.