The Berth Allocation and Quay Crane Assignment Problem Using a CP Approach

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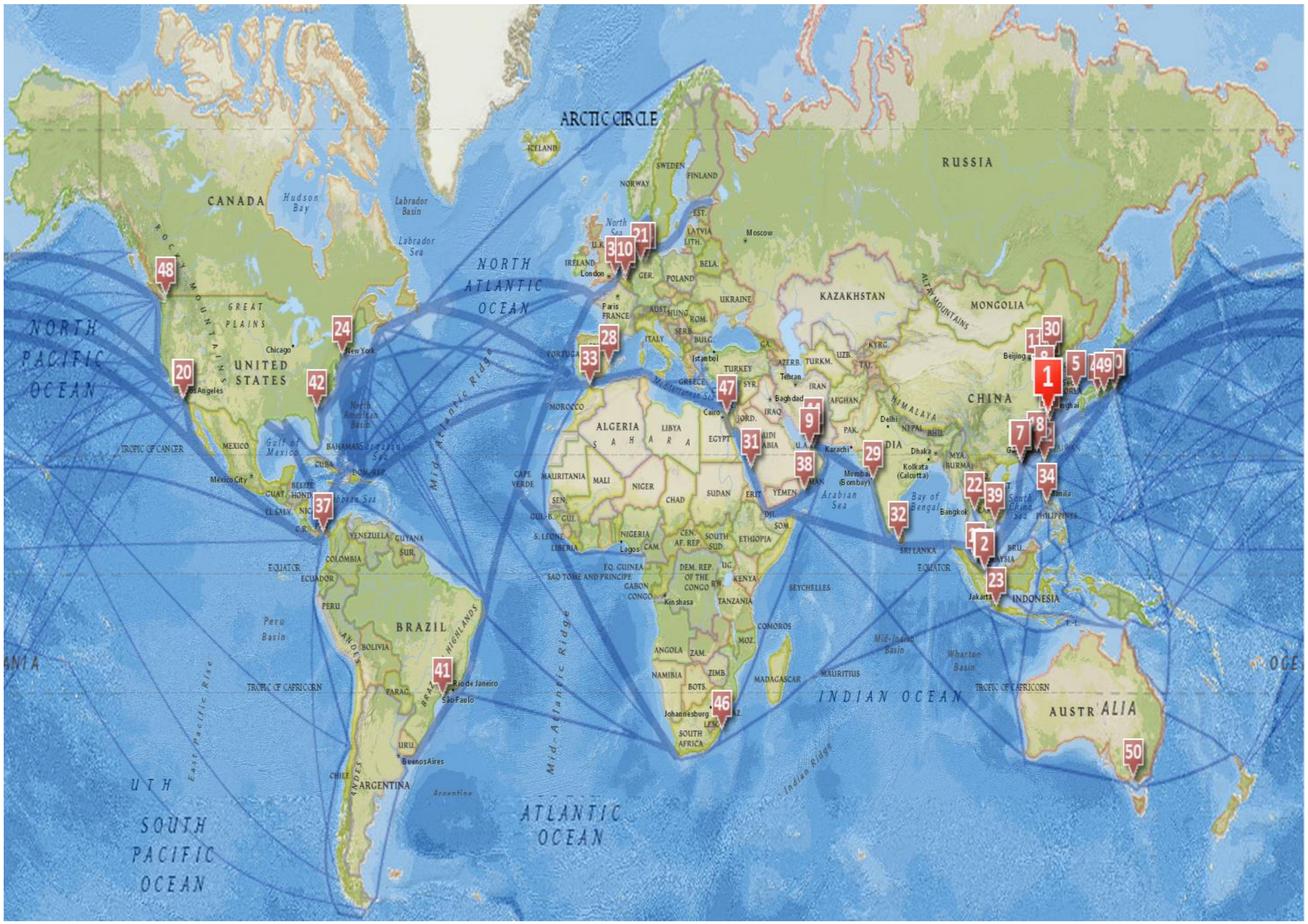
Summary

- Context - Container terminals
- Problem - Berth and Crane Allocation
- Model
- XP

Container terminals is a facility to move containers

- between ships, trucks and rails
- many types of containers but
  - 20'' and 40'' containers are the most common

90% of what we buy has been transported by container



Volumes TEUs 2011 in million

1. Shanghai, China
31,74
2. Singapore, Singapore
29,94
3. Hong Kong, China
24,38
4. Shenzhen, China
22,57
5. Busan, South Korea
16,16
6. Ningbo, China
14,72
7. Guangzhou, China
14,26
8. Qingdao, China
13,02
9. Dubai Ports, United Arab Emirates
12,62
10. Rotterdam, Netherlands
11,88

How does a terminal look like?

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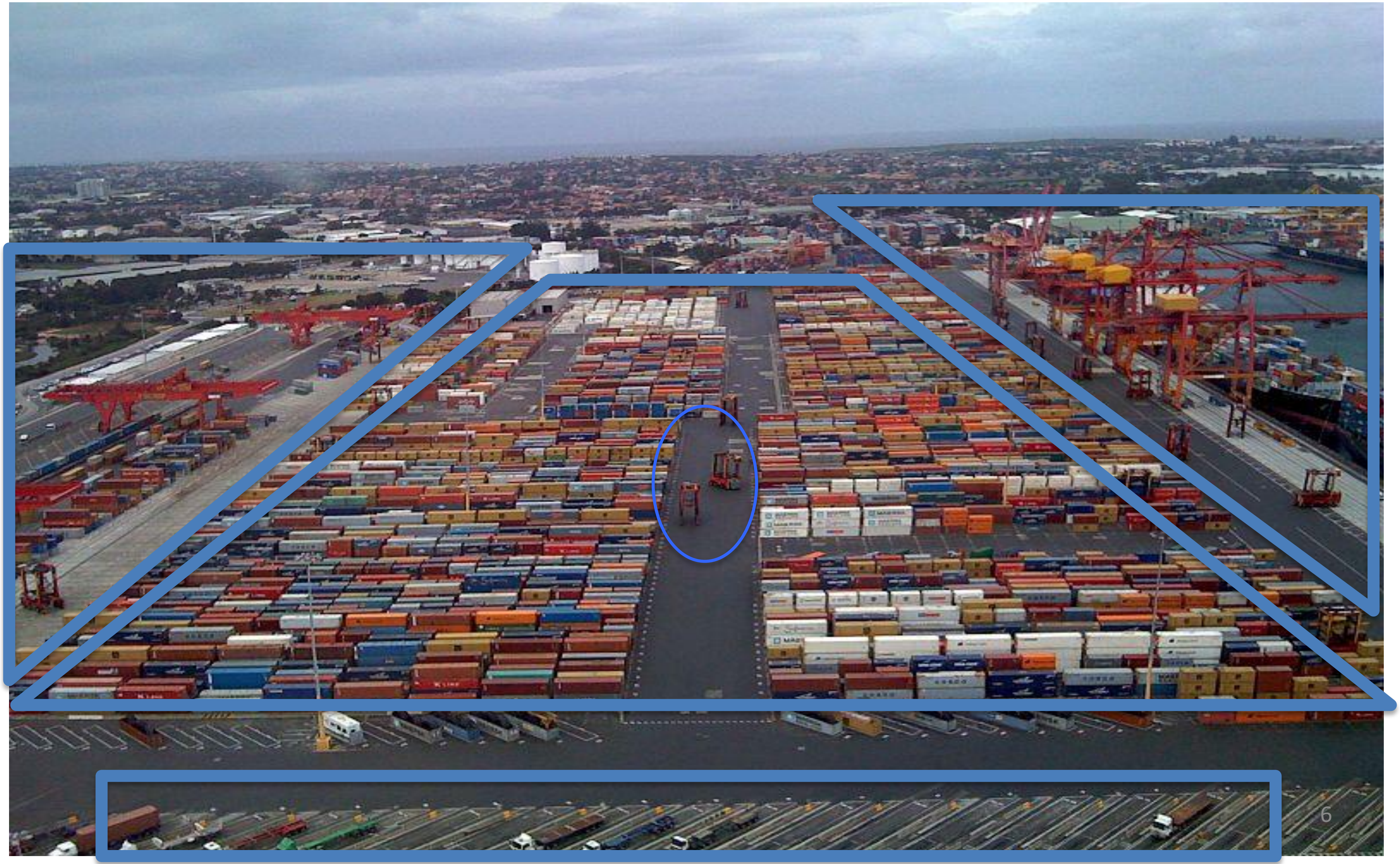
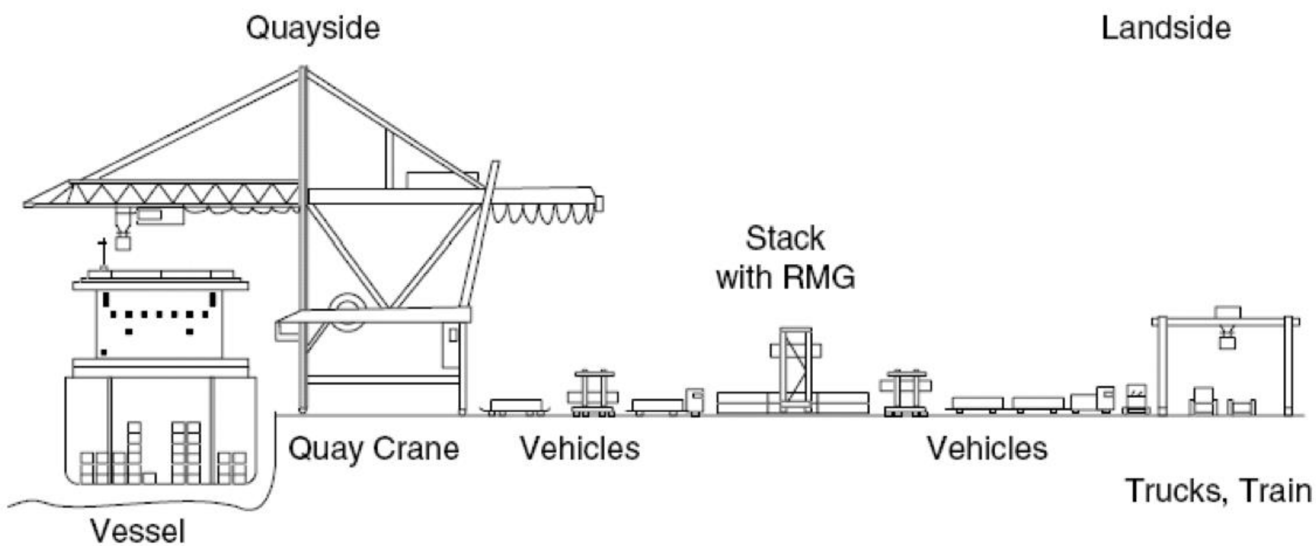


Terminal Schema



Optimization is crucial in terminals

Fully automated terminals under construction

- Winners will use the best optimization technology

Many optimization problems...

- Berth/Crane/Yard scheduling
- Horizontal transpotation dispatching
- (and many more)
- Real time/stochastic
- Scale: 1k-10k-100k variables
- Grail: holistic and stochastic approach

... where CP can play a key role

Affiliation

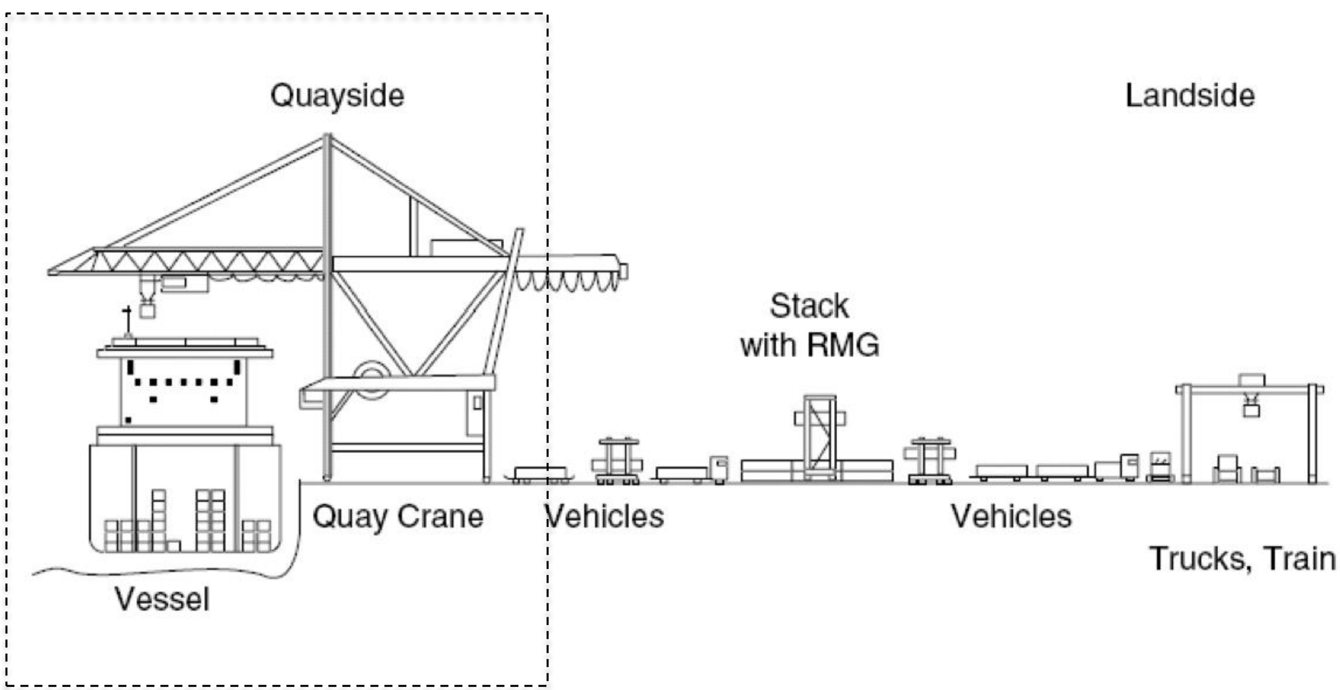
- Leader in the Terminal Operating System
- 25 yeard company
- Strategic Services (BI, Optimization, Processes)
- Investment in the Terminal Optimization
- Uses Ilog

Summary

- Context - Container terminals
- **Problem - BAPCAP**
- Model
- XP

Berth & Crane Assignment (BAPCAP)

We focus on single side of the terminal

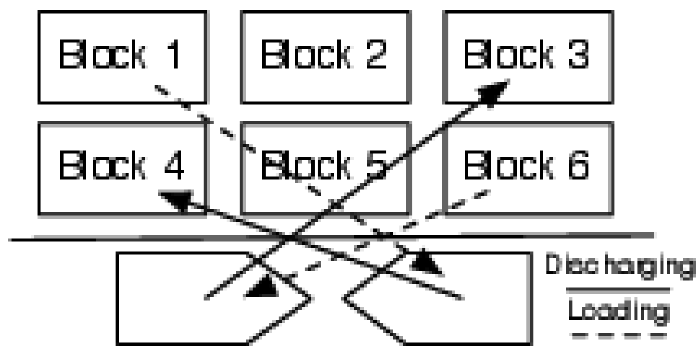


Berth Allocation Problem Input

- Ships are calling at the terminal
  - Length
  - Max number of cranes
  - List of containers to discharge
  - List of containers to load
  - Arrival time is known
  - Deadline imposed by shipping line
    - Any delay will incur (huge) fees paid by the terminal

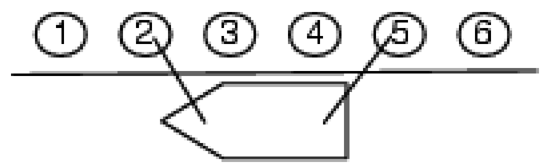
Berth Allocation Problem Input (2)

- Ideal berth position is precomputed from the yard



Berth Allocation Problem Decisions

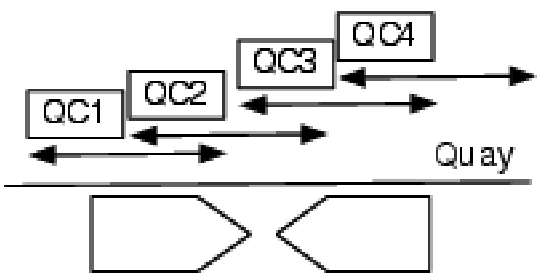
- Decide
  - Where to dock the vessel (discrete bollards)



  - Number of cranes to assign (<= max nbr)
    - duration = f(#containers,#cranes)
    - Cranes have a fixed productivity (35/h)

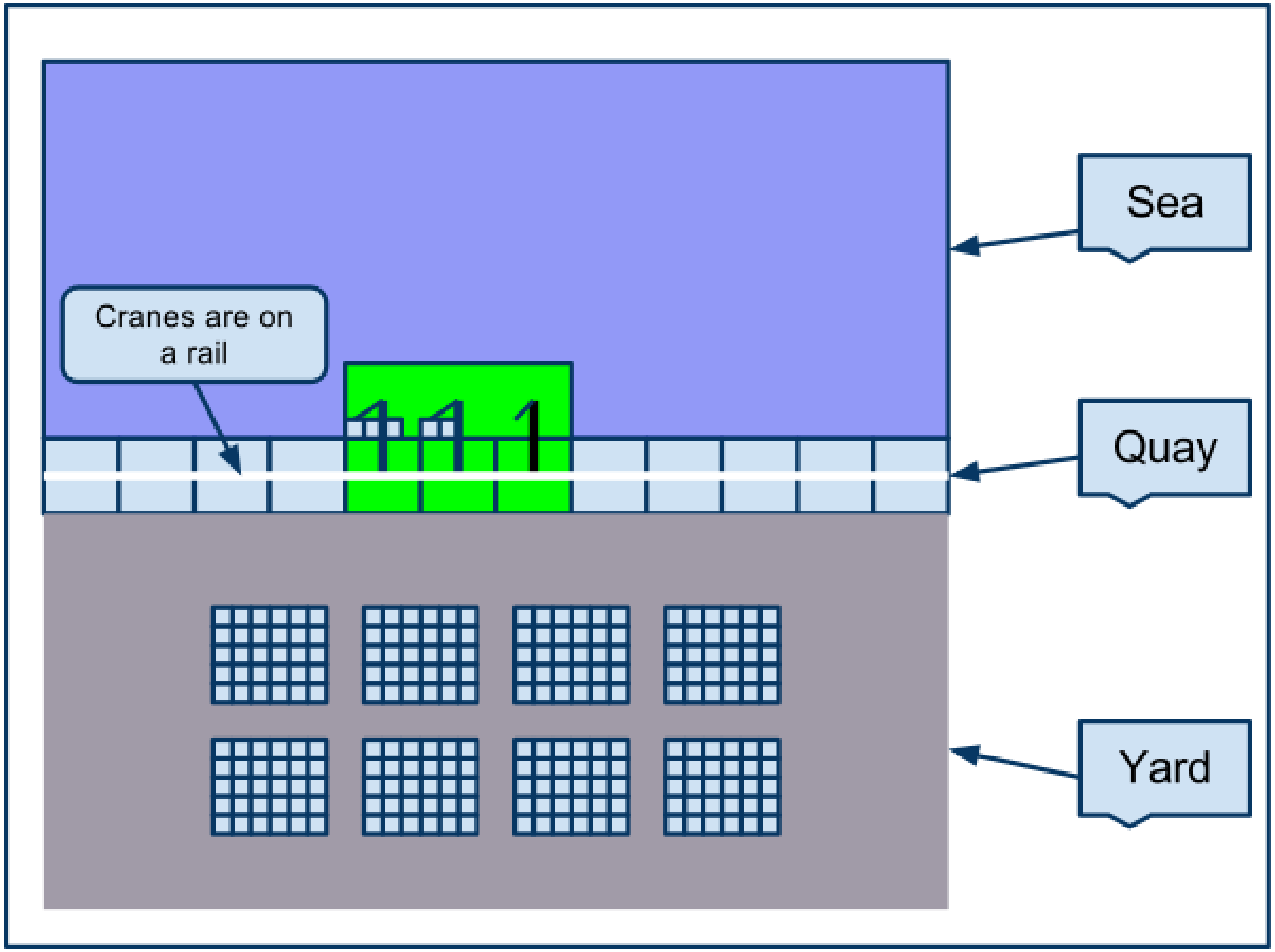
BAP Constraints and Objective

- Subject to
  - Max number of cranes along quay (18)
  - Suit quay length
  - Vessels should not overlap in time and space
  - Crane allocation is feasible (cranes on single rail)
  - Cranes have a range



- Minimize
  - Distance to ideal berth position
  - Lateness wrt imposed deadline

Cranes are operated on a rail



Typical BAP Solution in OR litterature

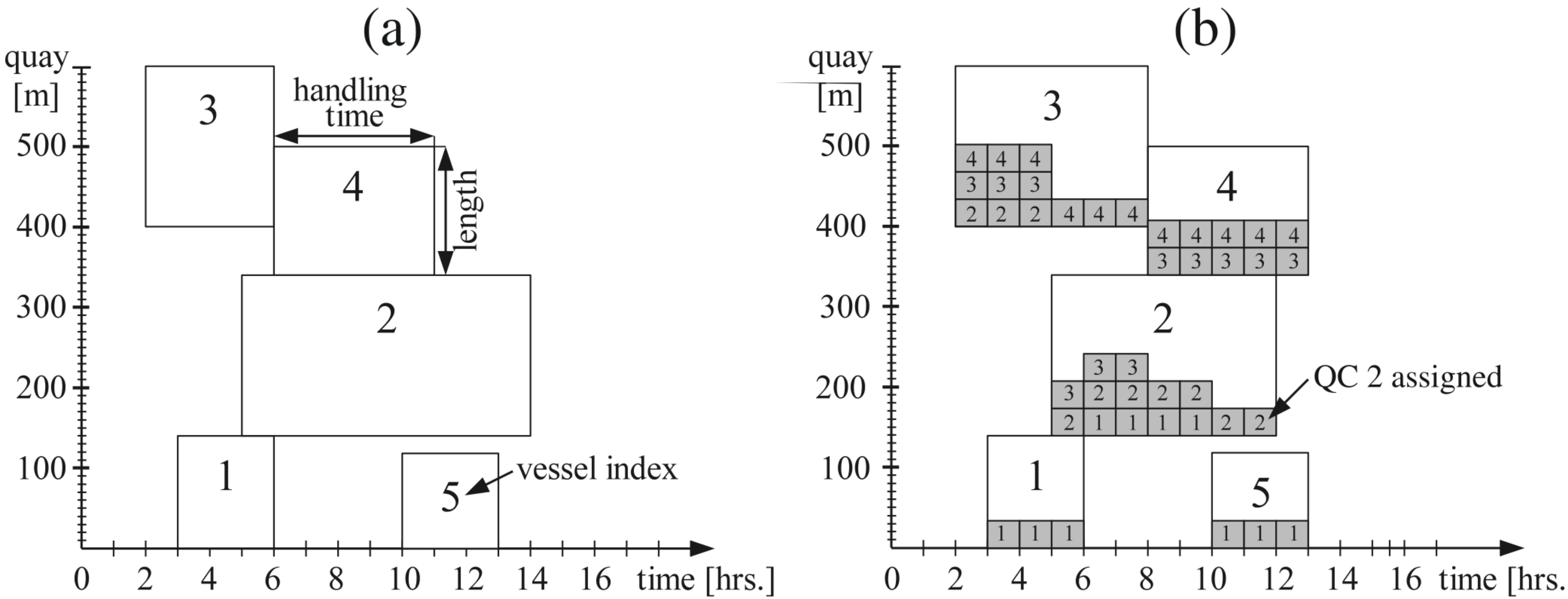


Fig. 2. Space-time representation of a berth plan (a), assignment of cranes to vessels (b).

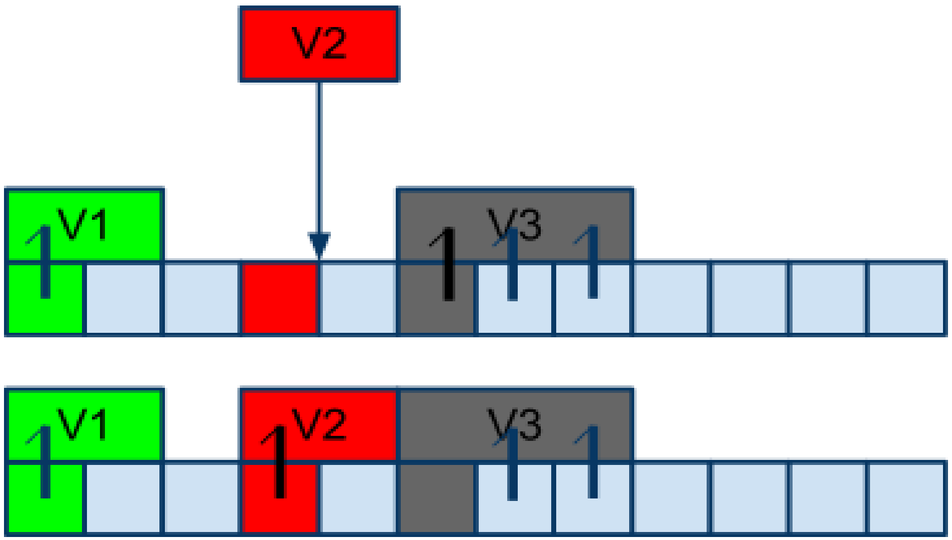
[Bierwirth & Meisel EJOR 202 (2010) 615–627]

Crane Assignment Problem

- Personel assignment to shifts of 8h
  - A gang is a team of workers for a crane
  - Assign gangs to cranes and cranes to vessels.
  - Hiring a gang has a fixed cost per shift
  - A gang is hired for an entire shift
  - Gangs can be moved from one crane to another
- Scheduling to the minute, no bucketization
- Preemptive schedule
  - quay crane can be moved at any point in time

Cranes can be reallocated

- Reallocating a crane can be done at any time

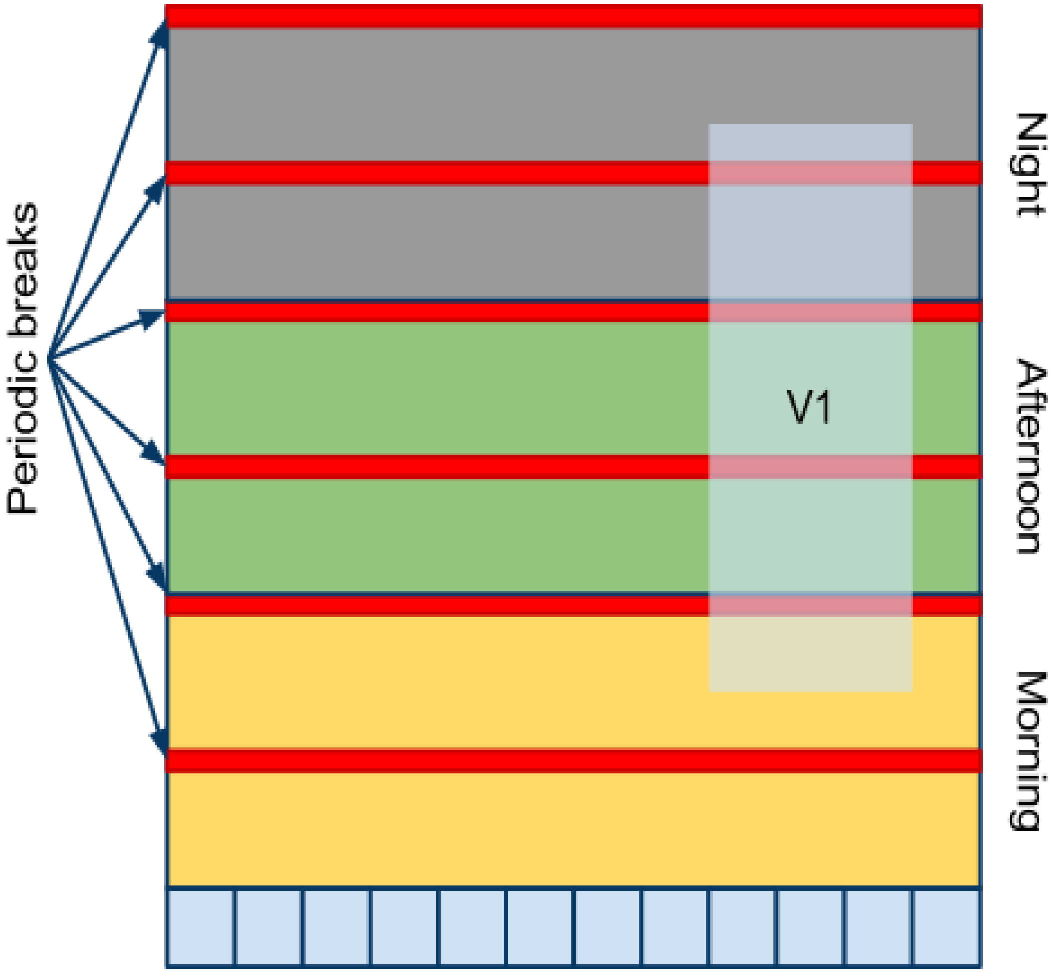


- Setup time to move the crane
  - Crane unavailable for 30 minutes
- Cranes can be moved freely during breaks

Gang Breaks and Cost

- Repositioning cranes from one vessel to another takes 30 minutes.
- Gangs have breaks. Each gang works for eight hours. Each gang has a break of half an hour each four hours.
- During this break, crane repositioning is free, handled by a specialized team.
- The gang cost per shift depends on the shift on which the gang operates.
- Gang costs must always be paid in full

Periodic Breaks



	Weekday	Saturday	Sunday
Morning	1.05	1.50	2
Afternoon	1.15	1.50	2
Night	1.50	2	2

Table 1: Relative cost of a gang

	Break 1	Break 2
Morning (06:00-14:00)	09:30-10:00	13:30-14:00
Afternoon (14:00-22:00)	17:30-18:00	21:30-22:00
Night (22:00-06:00)	01:30-02:00	05:30-06:00

Table 2: Gang shifts and breaks

KPI

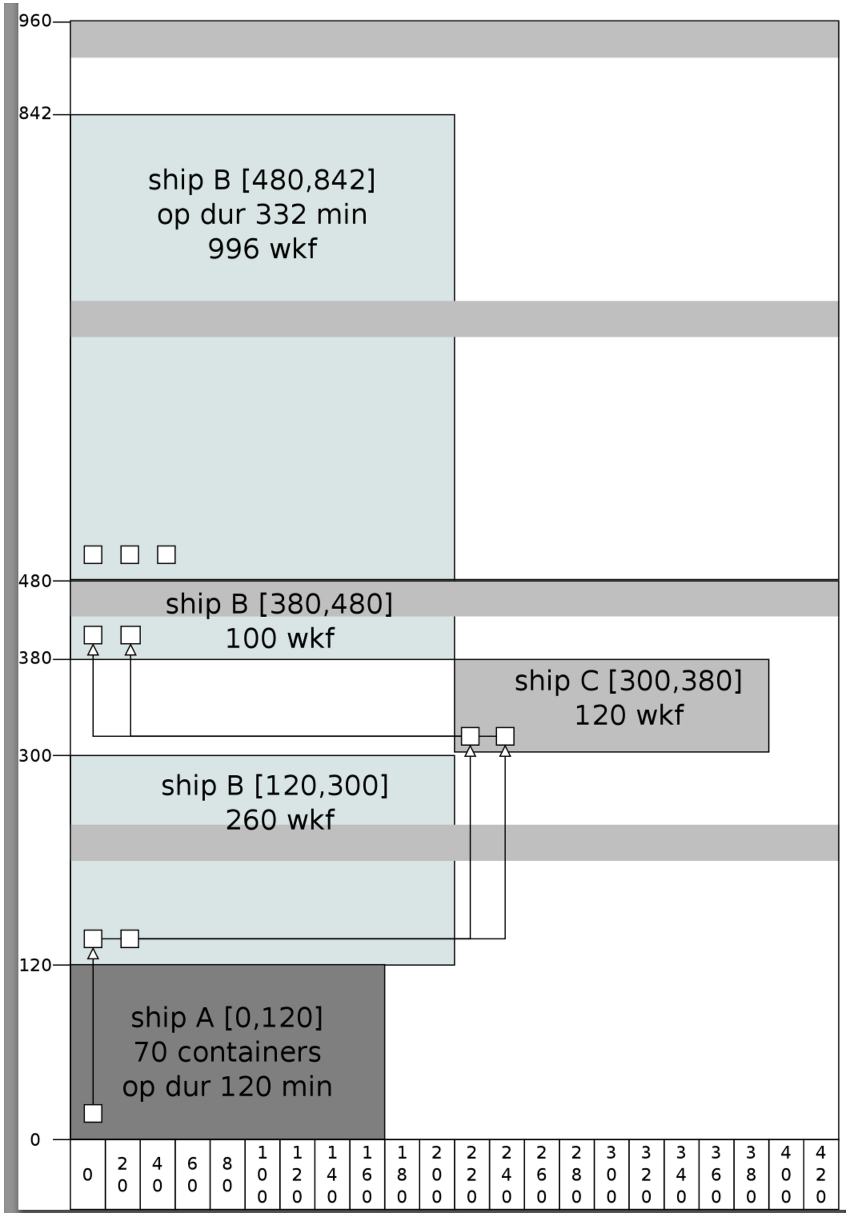
Three components:

- Lateness
  - max(0, activity[b].end – deadline[b])
- Diff Position
  - abs(pos[b] - idealPosition[b])
- Shift Cost
  - (# each type of shift) * (shift type cost)

We take a weighted sum

- Lateness is the most important
- For each component we multiple by the corresponding unit cost (in $)

Sample Solution



Challenge

Integrate both BAP and CAP into a single high fidelity model using all real world constraints (preemptive schedule, gangs, crane reallocation) and up to the minute (no bucketization).

OR approaches

- berth and crane integration challenging
- bucketized approach
- ignore real terminal costs
- do not scale to 30 vessels/5 days

Summary

- Context - Container terminals
- Problem - BAPCAP
- **Model**
- XP

Model Overview

Core Model
For each vessel, schedule tasks to gangs
Ignore crane and berth assignment

Berth Allocation
Ensure vessel can be placed in time and space

Crane Assignment
Ensure crane assignment is possible
Tractable

Recall how CP works

//1. Declare variables and domains

```
start_i = [0, horizon]
end_i = [0, horizon]
```

/*2*/ Minimize obj

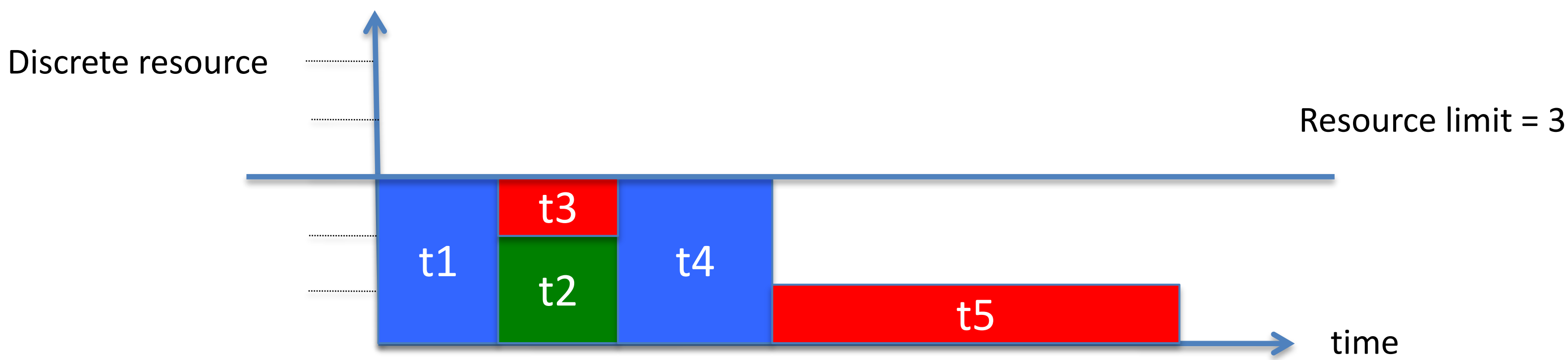
//3. State (global) constraints linking variables

```
Subject to {
    Start_i < end_i
    …
}
```

//4. Define Heuristics (optional)

Cumulative Global Constraint

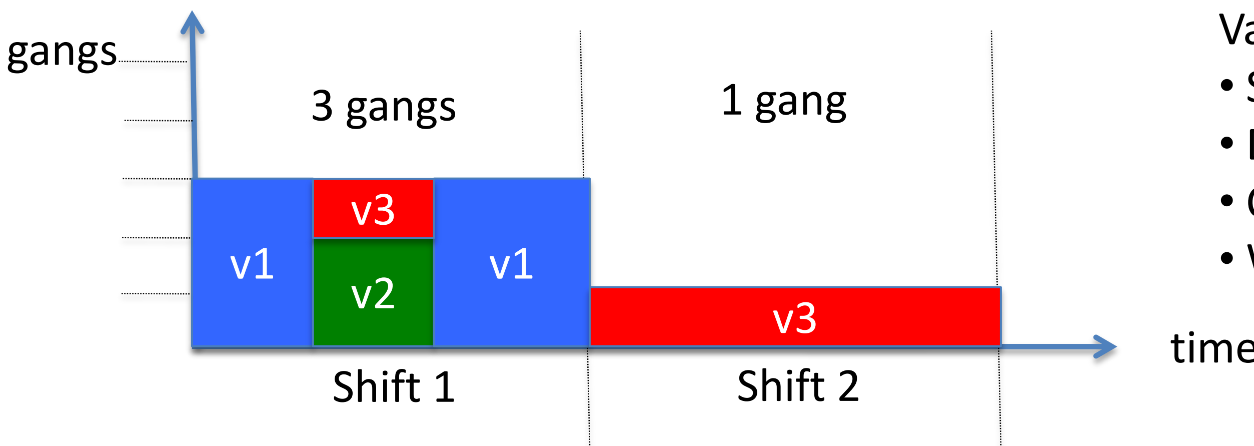
- Subproblem
  - Suppose that activities need to be scheduled but consume a fixed discrete amount of a discrete resource



- Signature: Cumu(A,k)
- A set of activities, where an activity is a set of variables:
  - start variable
  - duration variable
  - end variable
  - resource consumption variable

Core Model

- For each vessel, schedule activities over a cumulative resource of 18 gangs



Vars per activity:

- Start and end time
- Duration
- Capacity
- Workforce

- One cumulative per vessel, one global cumulative
- Each activity delivers a *workforce* (amount of work) (workforce <-> containers)
- Each vessel has to complete a required amount of workforce
- Each shift has a variable describing #gangs used using fake activities
- Preemptive schedule

Breaks and Transition Times

- The workforce of an activity depends on:
  - # gangs, duration, breaks and transition time
- Substract tt & breaks from duration of activity
  - 30 min are substracted to #gangs*duration
  - Activity starts with a break -> tt decreases
  - Wkf decreases when intersecting with breaks
  - Tt on the first activity accounts for setup time

Constraint 5 (Workforce) *For each activity (b, i), the workforce is*

$$wkf_{b,i} = (d_{b,i} - bi_{b,i} - tt_{b,i}) * cap_{b,i} \ .$$

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Starting/ending times
Gangs usage per shift

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Berth Allocation

- Each vessel has a position variable pos_b and a length $length_b$
- Each vessel has a starting time $s_b = \min s_{b,i}$
- Two vessels intersecting in time should not intersect in space:

Constraint 6 (Non-overlap) $\forall\ (b,c) \in vessels \times vessels, b > c : (s_b \leq e_c \wedge e_b \geq s_c) \vee (s_c \leq e_b \wedge e_c \geq s_b) \Rightarrow (pos_c \geq pos_b + length_b) \vee (pos_b \geq pos_c + length_c)$

Model Overview

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Berth Allocation

Ensure vessel can be placed in time and space

Berth position variables

Crane Assignment

Ensure crane assignment is possible

Tractable

Crane assignment

- Each activity has a crane range:

Definition 10 (Crane Range) *The crane range of an activity* (b, i) $(i \in Act_b)$ *is a range* $[sc_{b,i}, ec_{b,i}]$, *where* $sc_{b,i}$ *is the starting crane and* $ec_{b,i}$ *the ending crane.*

- Cranes cannot span the whole quay:

Constraint 7 (Crane Position) $\forall \; b \in vessels, i \in Act_b : sc_{b,i} \geq craneMin[pos_b]$ *and* $ec_{b,i} \leq craneMax[pos_b]$.

Crane assignment is tractable

- For each task intersecting in time, crane range follow their relative position:

$$[(s_{b,i} \leq e_{c,j} \wedge e_{b,i} \geq s_{c,j}) \vee (s_{c,j} \leq e_{b,i} \wedge e_{c,j} \geq s_{b,i}) \wedge \ (pos_b < pos_c)] \Rightarrow ec_{b,i} < sc_{c,j}$$

$$[(s_{b,i} \leq e_{c,j} \wedge e_{b,i} \geq s_{c,j}) \vee (s_{c,j} \leq e_{b,i} \wedge e_{c,j} \geq s_{b,i}) \wedge \ (pos_b > pos_c)] \Rightarrow sc_{b,i} > ec_{c,j}$$

- Once the position, #cranes, starting and ending time are labeled, the crane assignment constraints form a linear chain of inequality constraints
- The crane assignment submodel is *tractable*
- Do no label the crane variables, come for free!

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Berth position variables

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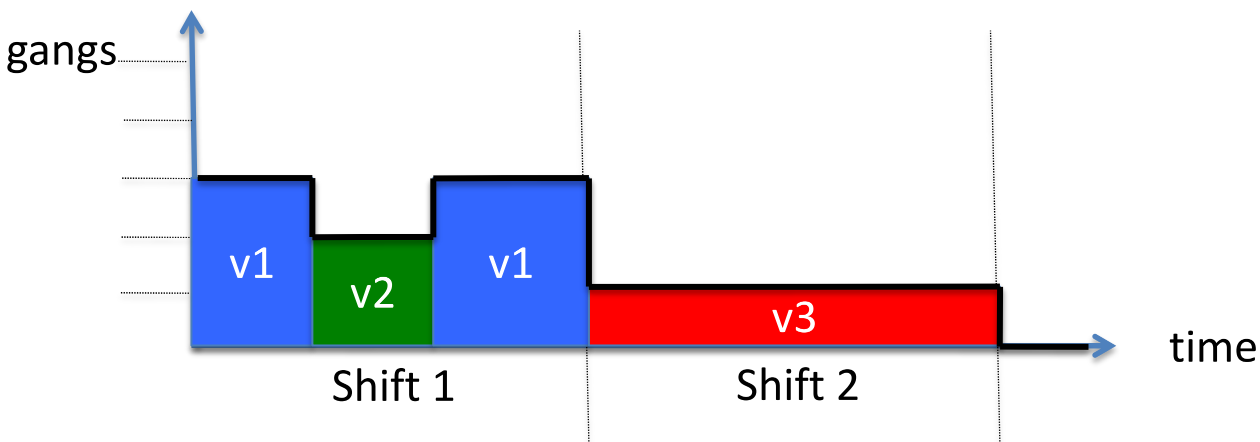
Crane assignment variables

Fill Hole Heuristics

- For each vessel in arrival time order
  - Fill holes in the cumu profile [De Clercq & al, CP2011]



- Assign a position to the vessel along the quay
- Crane assignment checking done automatically
- LNS where entire vessels are fixed with a 0.6 probability

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MIP Relaxation

- Gang allocation relaxed into an integer program
  - Minimize total gang cost where required workforce is distributed in elligible shifts
- Ignore all other constraints:
  - Crane allocation and space allocation ignored
  - Cranes can reach any vessel, can cross each other and can move instantly.
  - Vessels can overlap along the quay.
  - Breaks & transition times
- The MIP model considers cranes are helicopters and vessels can be positioned anywhere.
- Low lower bound

Computational Results

	Time (sec)		GAP	Objective Value				Extra Gangs
H	CP	MIP		Total	Gang	Pos.	L.	
Random1, 10 vessels								
FH	504	600	7.8	20648	20589	59	0	5(67/62)
naive	600	600	-	-	-	-	-	-
FHR	175	243	0.4	18522	18522	0	0	0(62/62)
Random2, 10 vessels								
FH	483	8	11.0	20553	20446	107	0	6(65/59)
naive	385	7	27.8	25356	25321	35	0	7(66/59)
FHR	93	6	0.4	18314	18314	0	0	0(59/59)
Random3, 10 vessels								
FH	542	343	18.8	36433	36265	168	0	12(104/92)
naive	600	356	-	-	-	-	-	-
FHR	364	600	0.7	28587	28587	0	0	0(92/92)

	Time (sec)		GAP	Objective Value				Extra Gangs
H	CP	MIP		Total	Gang	Pos.	L.	
Random4, 10 vessels								
FH	582	600	13.6	29998	29473	525	0	6(86/80)
naive	600	600	-	-	-	-	-	-
FHR	211	600	0.4	26509	26509	0	0	0(80/80)
Industrial, 15 vessels								
FH	458	2	11.9	15857	15666	191	0	4(48/44)
naive	428	3	23.3	18209	18078	131	0	8(52/44)
FHR	501	2	0.9	14030	14030	0	0	0(44/44)
Industrial, 30 vessels								
FH	60	12	16.5	29884	29050	834	0	11(90/79)
naive	338	12	41.1	42335	41530	805	0	26(105/79)
FHR	12	11	1.8	25878	25878	0	0	1(80/79)

Table 3: Results for all instances.

Conclusion

- Container terminal is a rich application field
- High fidelity can be integrated using CP
- 10 to 20% distance from an ideal operational setting
- Nice CP case for the OR community

The Berth Allocation and Quay Crane Assignment Problem Using a CP Approach

Questions?