Exact Solution Approaches to the Berth Allocation Problem in Bulk Sea Port Terminals

IFORS Conference, July 14th, 2011

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Outline

- **Motivation**
- **Introduction to bulk ports**
  - Bulk port operations and equipment
  - Case Study of SAQR
- **Research Challenges and Objectives**
- **Berth Allocation Model**
  - Mixed Integer Linear Model
  - Set Partitioning Approach
- **Preliminary Results and Analysis**
- **Conclusions and Future Work**

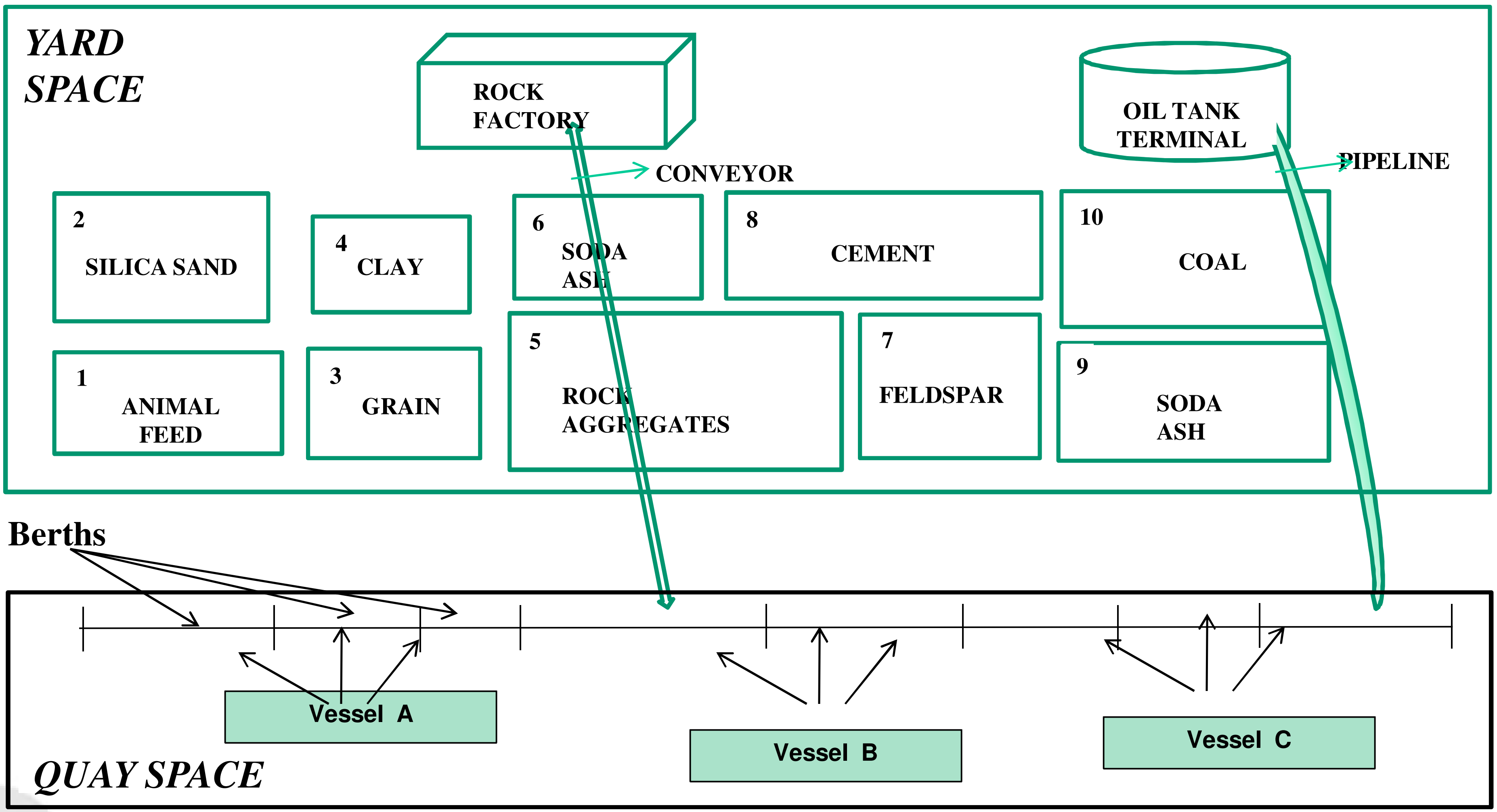
Motivation

- Bulk port terminals have received significantly less attention than container terminals in the field of large scale optimization

- High level of uncertainty in bulk port operations due to weather conditions, mechanical problems etc.
  - Disrupt the normal functioning of the port
  - Require quick real time action.

- The major objective of planning robust port operations is to minimize operational costs while maximizing system reliability.

Schematic Diagram of a Bulk Terminal



Bulk terminal operations

- **Vessel and Berth Activities**

- **Ship Loading or Discharge**

- Apron to Storage Transfer

Pipelines

Loading Shovels

Wheel loaders

- Storage

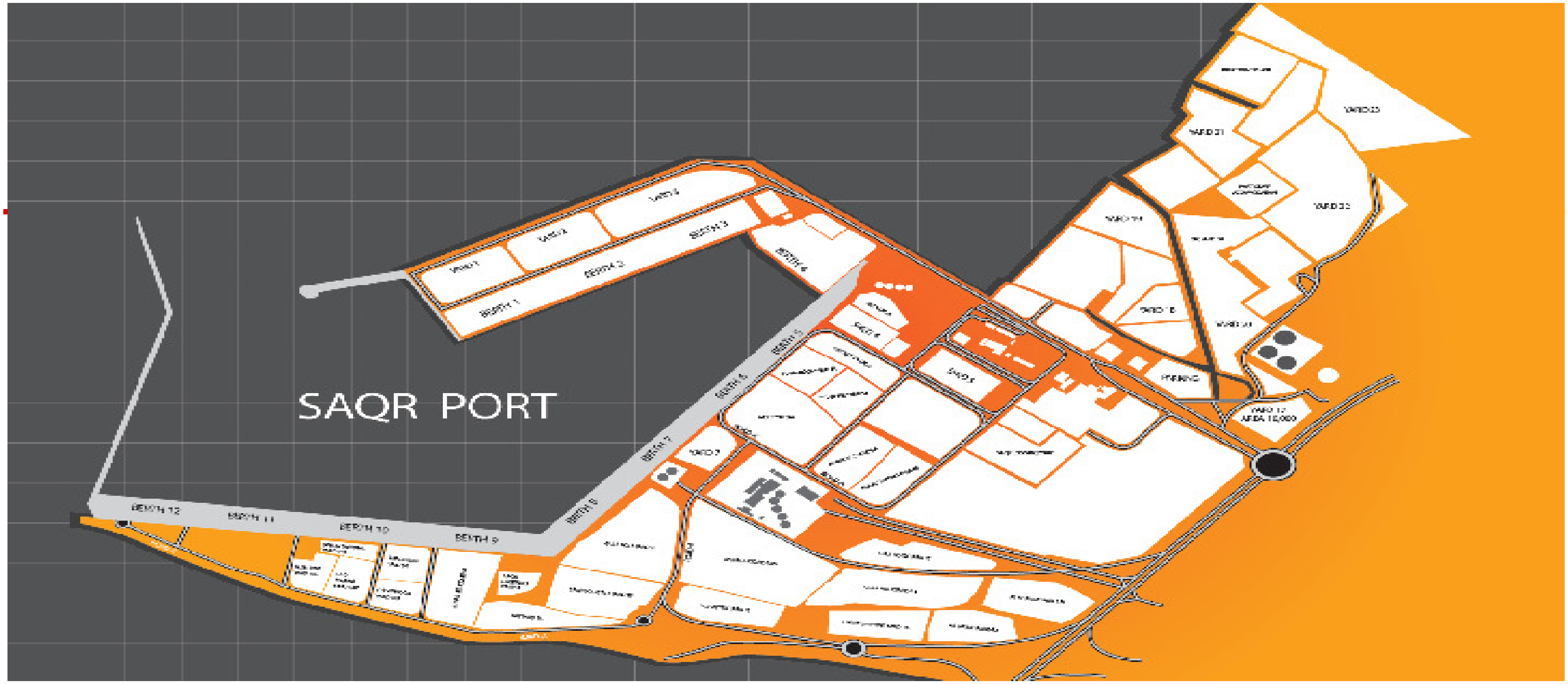
- Intermodal transfer and inland distribution

Case Study: SAQR Port, Ras Al Khaimah, UAE

- Biggest bulk port in the entire middle east, handling 30 million tons of bulk and assorted cargo annually

- Deals with a wide variety of imported and exported commodities- aggregates, cement, coal, clinker, iron ore, feldspar, clay, soda ash, petroleum products etc.

- Wide range of equipment facilities including MHC’s, load shovels, mini, wheel and ship loaders etc.



- **Port Layout**
  - 12 berths, with alongside depth of 12.2 meters at mean low water spring tide
  - 8 x 200 meters bulk handling berths, 3 x 200 meters container handling berths and 1 general purpose roll-on/roll-off berth
  - Conveyors at berths 5 and 7; pipelines at berths 6,7 and 11 (variable demand across different berths)

Research challenges

- **Key issues and sources of disruption at SAQR**: High waiting times and delays at berths owing to
  - Congestion at berths
  - Unavailability of required number and type of equipment when needed
  - *Uncertainty in arrivals* of vessels and cargo trucks

Research Objectives

- ***Integration of the two crucial problems of berth allocation and yard allocation*** for better coordination between berthing and yard activities

- Include ***robustness*** in planning process to account for uncertainties in arrival times of vessels and cargo trucks which lead to unforeseen disruptions and delays in operations.

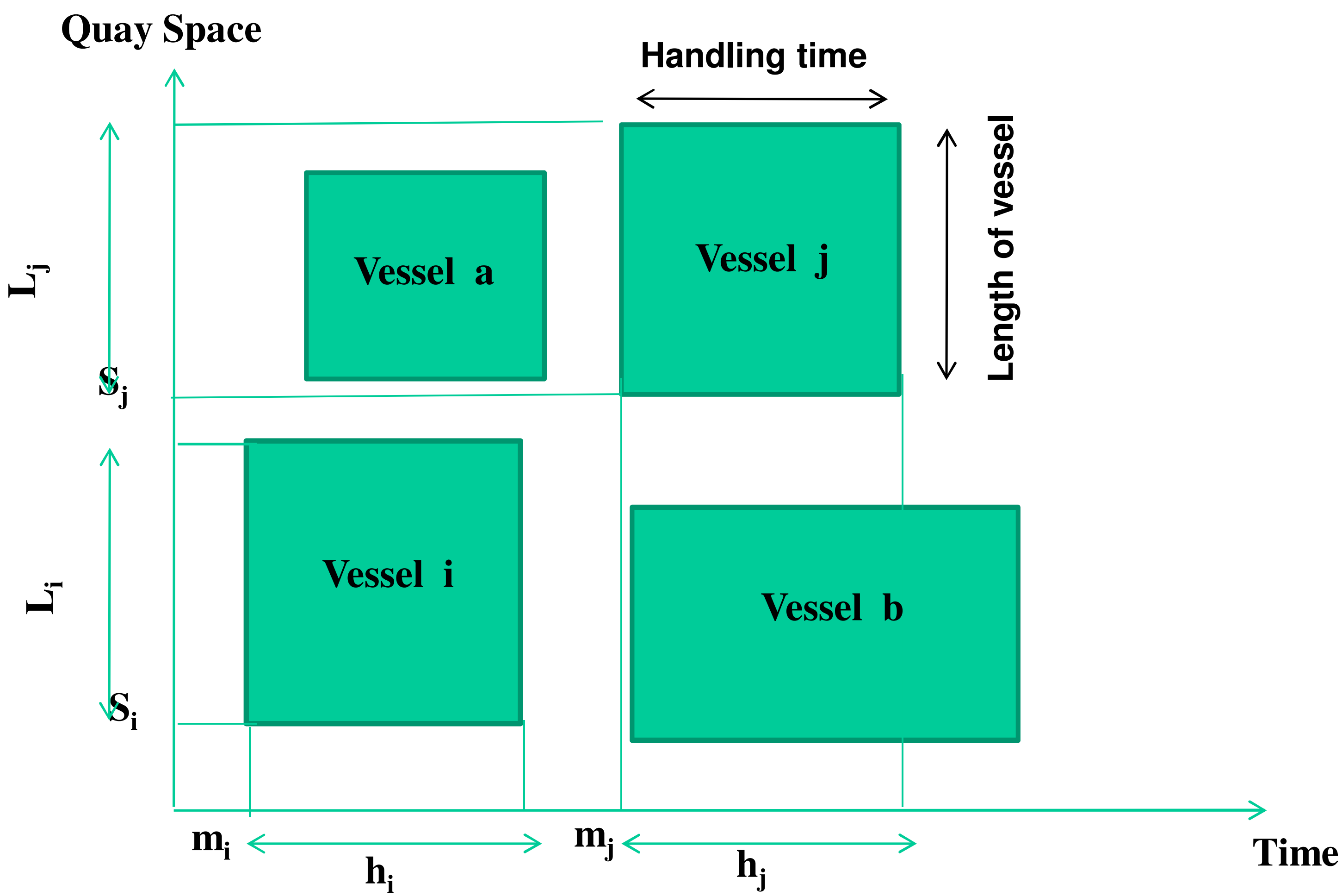
- Develop methodologies and algorithms that can be extended to other domains such as container ports, railways and airlines.

The Berth Allocation Problem

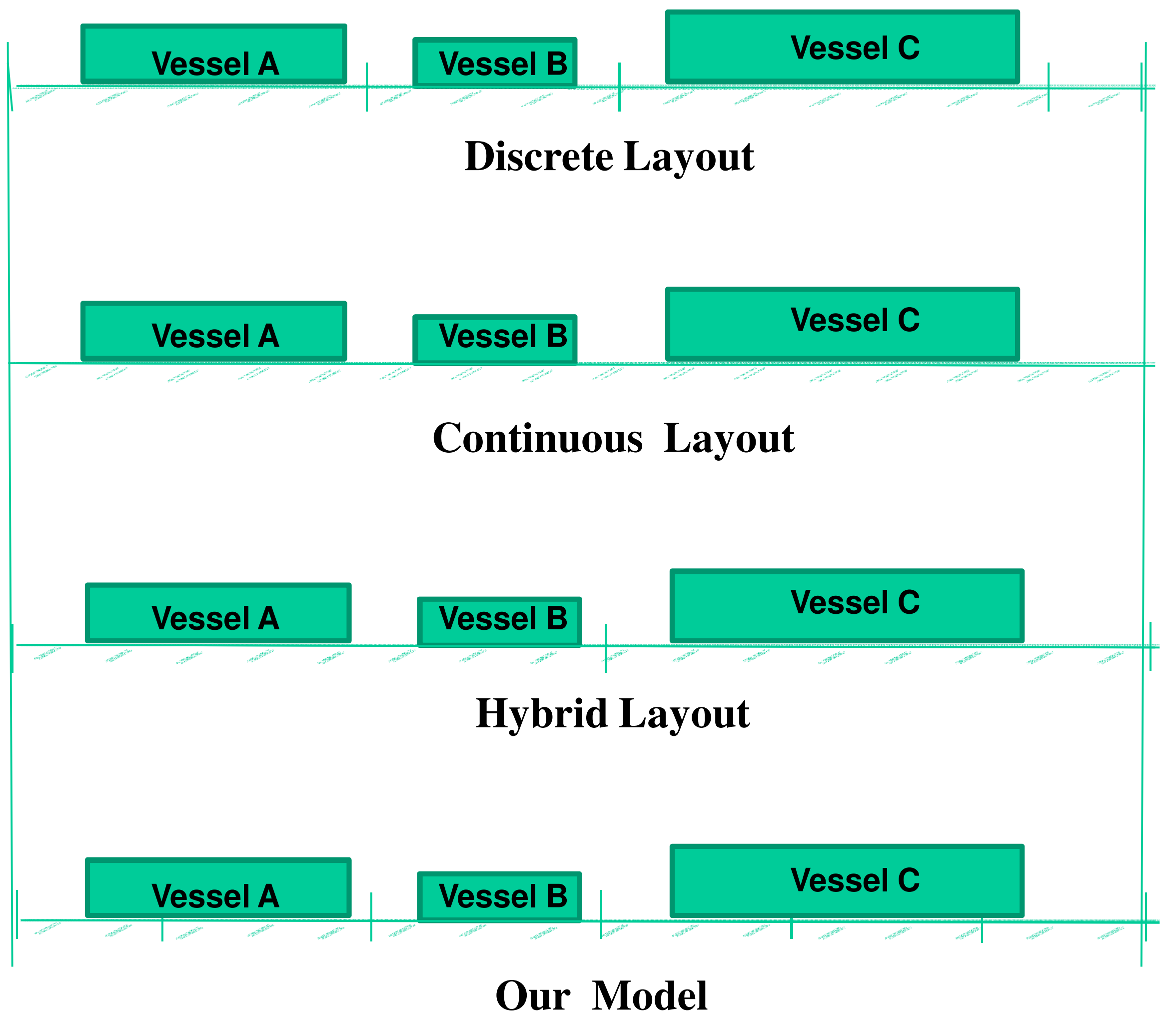
Problem Definition

- **Find**
  - Berthing assignment and schedule of vessels along the quay
- **Given**
  - Time windows on arrivals of vessels
  - Handling times dependent on berthing position and cargo type
- **Objective**
  - Minimize total service times of vessels berthing at the port

BAP Solution



Discretization



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BAP Model

Objective Function

$$\min \sum_{i \in N} (m_i - a_i + h_i)$$

Decision variables:

m_i	starting time of handling of vessel $i \in N$;
a_i	arrival time of vessel $i \in N$;
h_i	total handling time of vessel $i \in N$;

BAP Model

Dynamic vessel arrival constraints

$$m_i - a_i \geq 0 \qquad \forall i \in N,$$
$$a_i = A_i r_i + U_i (1 - r_i) \qquad \forall i \in N,$$

A_i expected arrival time of vessel $i \in N$;

U_i upper bound to the arrival time of vessel $i \in N$;

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BAP Model

Non overlapping constraints

$$\sum_{k\in M}(b_k s_k^j) + B(1-y_{ij}) \geq \sum_{k\in M}(b_k s_k^i) + L_i \qquad \forall i, j \in N, i \neq j,$$

$$m_j + B(1-z_{ij}) \geq m_i + C_i \qquad \forall i, j \in N, i \neq j,$$

$$y_{ij} + y_{ji} + z_{ij} + z_{ji} \geq 1 \qquad \forall i, j \in N, i \neq j,$$

Section covering constraints

$$\sum_{k\in M} s_k^i \geq 1 \qquad \forall i \in N,$$

$$\sum_{k\in M} (b_k s_i^k) + L_i \leq L \qquad \forall i \in N,$$

$$\sum_{p\in M} x_{ipk} s_p^i = x_{ik} \qquad \forall i \in N, \forall k \in M,$$

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BAP Model

Draft Restrictions

$$(d_k - D_i)x_{ik} \geq 0 \qquad \forall i \in N, \forall k \in M,$$

Determination of Handling Times

$$h_i \geq h_k^{iw} p_{ilk} Q_i s_l^i \qquad \forall i \in N, \forall k \in M, \forall l \in M, \forall w \in W_i$$

Q_i quantity of cargo to be loaded on or discharged from vessel *i*

h_k^{iw} handling time for unit quantity of cargo $w \in$ when vessel $i \in N$ is berthed in section $k \in M$;

Generation of Instances

- Instances based on data from SAQR port
  - Quay length of 1600 meters and vessel lengths in the range 80-260 meters
- Test instances for $|N|$ = 5,10 and 15 vessels, and $|M|$ = 10,20 and 30 sections
- Rate of handling is 15 hours per 10^4 tonnes per crane, and number of cranes dependent on length of each section
- Drafts of all vessels D_i are less than the minimum draft along the quay.
- Instances solved using commercially available CPLEX 12.1 solver!

Preliminary Results and Analysis

|*N*| = 5 vessels, and |*M*| = 10,20 and 30 sections

5 x 10	**obj**	**t(s)**
Large Time Horizon	52.50	0.34
Medium Time Horizon	52.50	0.27
Small Time Horizon	60.00	0.50
5 x 20		
Large Time Horizon	66.59	0.53
Medium Time Horizon	66.59	0.48
Small Time Horizon	66.59	0.43
5 x 30		
Large Time Horizon	66.59	0.61
Medium Time Horizon	66.59	0.47
Small Time Horizon	66.59	0.64

- All instances solved in less than a second

|N| = 10 vessels, and *|M|* = 10,20 and 30 sections

10 x 10	obj	t(s)
Large Time Horizon	106.79	8.64
Medium Time Horizon	115.74	1532.06
Small Time Horizon	128.78	1746.41
10 x 20		
Large Time Horizon	121.35	2.67
Medium Time Horizon	124.98	41.01
Small Time Horizon	136.03	4556.36
10 x 30		
Large Time Horizon	117.50	2.88
Medium Time Horizon	119.95	3.63
Small Time Horizon	123.60	17.56

- All (except one)instances solved within 1 hour of computation time

$|N|$ = 15 vessels, and $|M|$ = 10,20 and 30 sections

15x 10	obj	gap	t(s)
Large Time Horizon	119.23	4.98%	3600
Medium Time Horizon	136.66	17.67%	3600
Small Time Horizon	166.82	30.09%	3600
15 x 20			
Large Time Horizon	134.42	0.00%	39.14
Medium Time Horizon	138.79	1.78%	3600
Small Time Horizon	179.25	21.94%	3600
15 x 30			
Large Time Horizon	133.26	0.00%	15.12
Medium Time Horizon	156.33	14.00%	3600
Small Time Horizon	198.73	30.39%	3600

- Very few instances solved within CPLEX time limit of 1 hour!

Sensitivity Analysis: Effect of discretization and congestion!

$|N|$ = 10 vessels, and $|M|$ = 10,20 and 30 sections

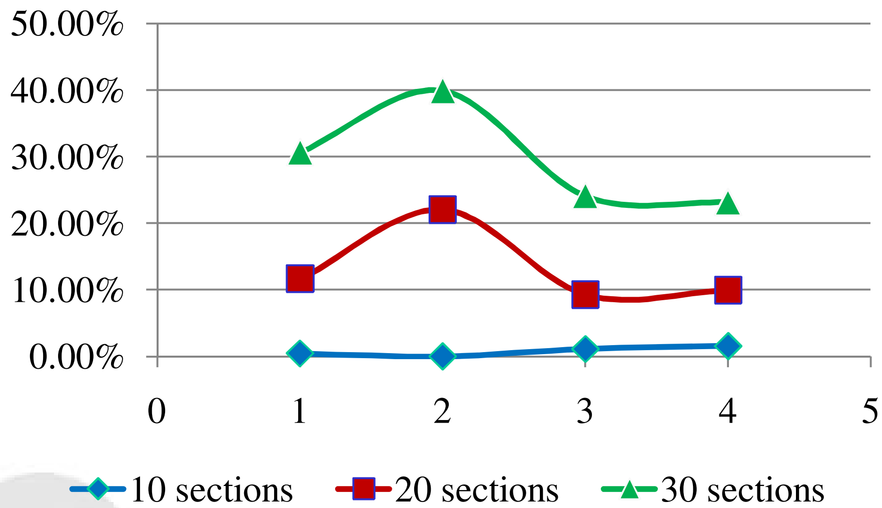
	Discretization I		Discretization II	
10 x 10	**obj**	**t(s)**	**obj**	**t(s)**
congestion free	104.71	0.38	106.79	8.64
mildly congested	105.70	3.98	115.74	1532.06
congested	118.39	537.48	128.78	1746.41
10 x 20				
congestion free	108.49	3.83	121.35	2.67
mildly congested	110.82	17.08	124.98	41.01
congested	123.56	437.02	136.03	4556.36
10 x 30				
congestion free	118.84	1.87	117.50	2.88
mildly congested	119.55	2.38	119.95	3.63
congested	127.60	19.78	123.60	17.56

- Increase in objective function value and computation time with congestion!
- Discretization I better than II

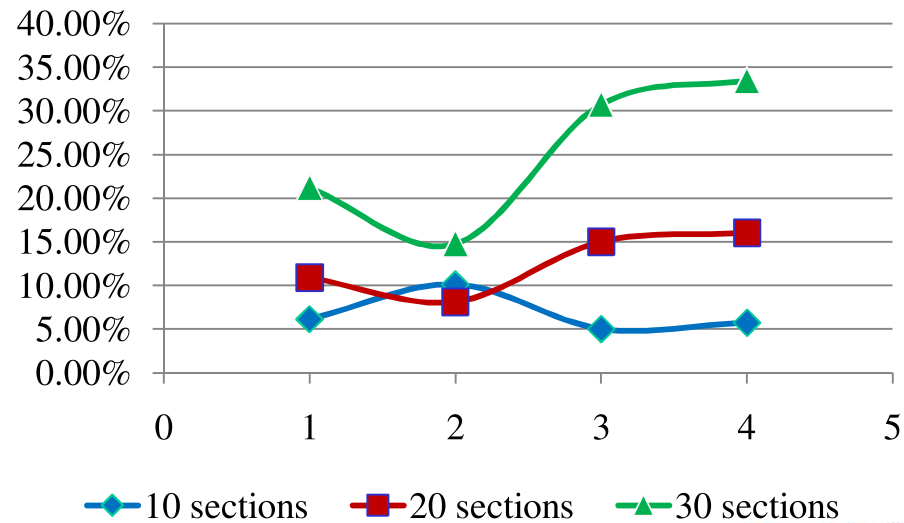
Sensitivity Analysis: Effect of vessel length

- Test for 4 pairs of instances with everything same except vessel lengths
  - one instance with vessel lengths in the range 80 -120 meters with vessel arrivals close together
  - other instance with vessel lengths in the range 180-220 meters with vessel arrivals close together

5 vessels : % difference in OFV for long and small vessels



10 vessels : % difference in OFV for long and small vessels



Generalized Set Partitioning Model

- Used in context of container terminals by Christensen and Holst (2008)

- Generate set P of columns, where each column $p \in P$ represents a feasible assignment of a single vessel in both space and time

- Generate two matrices

  - Matrix A = (A_{ip}) ; equal to 1 if vessel $i \in N$ is the assigned vessel in the feasible assignment represented by column $p \in P$

  - Matrix B = (b_p^{st}) ; equal to 1 if section $s \in M$ is occupied at time $t \in H$ in column $p \in P$

Note: Assume integer values for all time measurements

GSPP Model Formulation

Objective Function:

$$\min \sum_{p \in P} (d_p \lambda_p + h_p \lambda_p)$$

Constraints:

$$\sum_{p \in P} (A_{ip} \lambda_p) = 1 \qquad \forall i \in N$$

$$\sum_{p \in P} (b_p^{st} \lambda_p) \leq 1 \qquad \forall s \in M, \forall t \in H$$

d_p : *delay in service associated with assignment* $p \in P$

h_p : *handling time associated with assignment* $p \in P$

λ_p : binary parameter, equal to 1 if assignment $p \in P$ is part of the optimal solution

Comparison between GSPP and MILP formulations

		MILP	GSPP	
10 x 10	obj	t(s)	t(s)	
congestion free	106.79	8.64	0.28	
mildly congested	115.74	1532.06	0.32	
congested	128.78	1746.41	0.27	
10 x 20				
congestion free	121.35	2.67	1.30	
mildly congested	124.98	41.01	1.54	
congested	136.03	4556.36	2.66	
10 x 30				
congestion free	117.50	2.88	%	
mildly congested	119.95	3.63	%	
congested	123.60	17.56	%	
15 x 10			obj	time
congestion free	119.23 (4.98%)	3600	119.73	0.33
mildly congested	136.66 (17.67%)	3600	129.73	0.34
congested	166.82 (30.09%)	3600	156.45	0.79

- GSPP model is very fast, but memory issues due to large number of variables
- For small planning horizon, GSPP model can solve very big instances

Summary of Results

- Preliminary results inspired by port data show that the problem is complex and general purpose solvers fail to produce good solutions as soon as the problem size increases.
- Sensitivity Analysis
  - Choosing the most appropriate discretization is critical!
  - Complexity increases significantly when vessel arrivals are close together!
  - Optimal Objective Function Value is more sensitive to vessel lengths for larger number of sections
  - Limitations: It can only be performed for small instance sizes up to 10 vessels.
- GSPP approach is extremely fast, but memory issues for large instances

Ongoing and Future Work

- Experimental Analysis
  - Impact of parameters
  - Robust vs. Non-Robust: For given berthing schedule, test different scenarios of arrival delays and different distributions for arrivals times (such as triangular , uniform etc.)
- For bigger sized instances
  - Use dynamic column generation approach to resolve memory issues with the GSPP Model
  - Possibly explore heuristic approaches for faster results
- Integration of the berth allocation problem with yard allocation

Thank you!