Brunel University London
Brunel Business School

This project receives funding in the European Commission's Horizon 2020 Research Program under Grant Agreement Number 769267

Sustainability considerations in container pre-marshalling problem

EURO2021, Athens (hybrid), University of West Attica, 11-14 July 2021

Cihan Bütün

Afshin Mansouri

Ran Wang

Brunel Business School

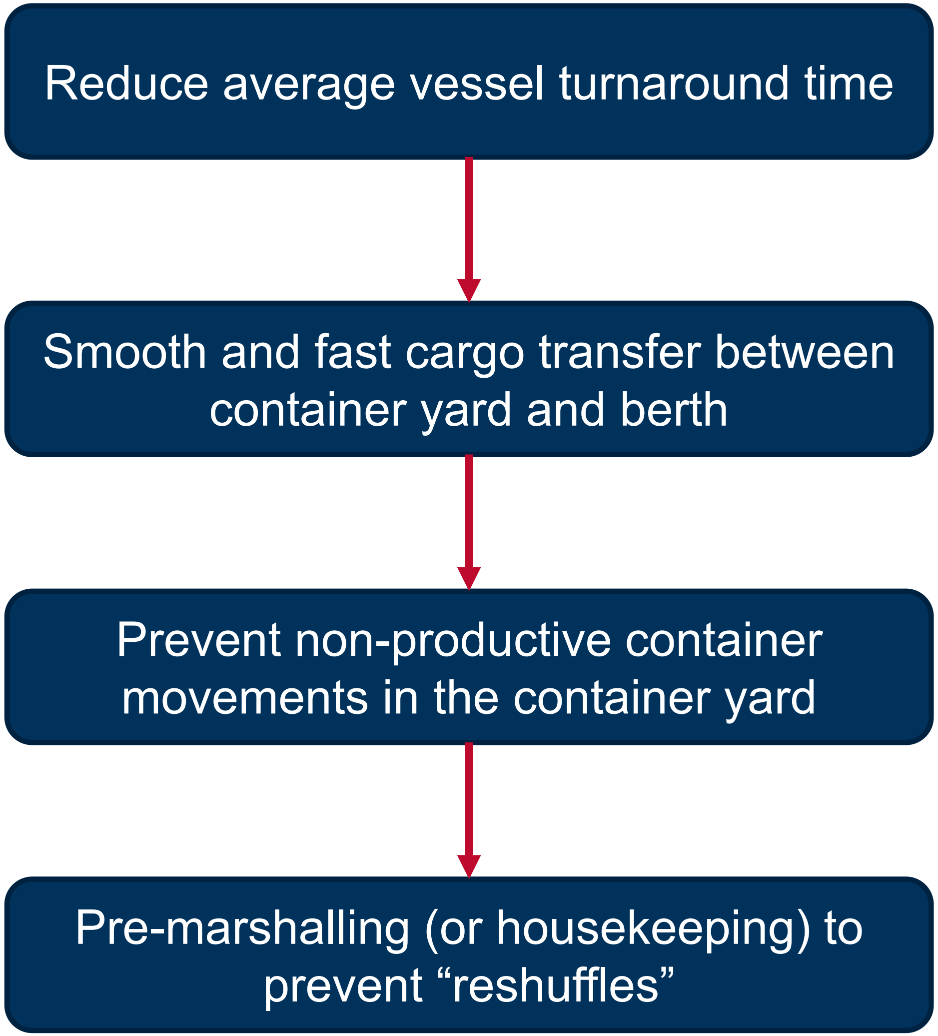
Brunel University London

Agenda

- Research motivations
- Problem definition & literature review
- Model formulation
- Solution heuristic development
- Computational experiments
- Conclusions

Research motivations

(Source: https://www.termavi.com/en/multimedia-2/)



Reduce average vessel turnaround time

Smooth and fast cargo transfer between container yard and berth

Prevent non-productive container movements in the container yard

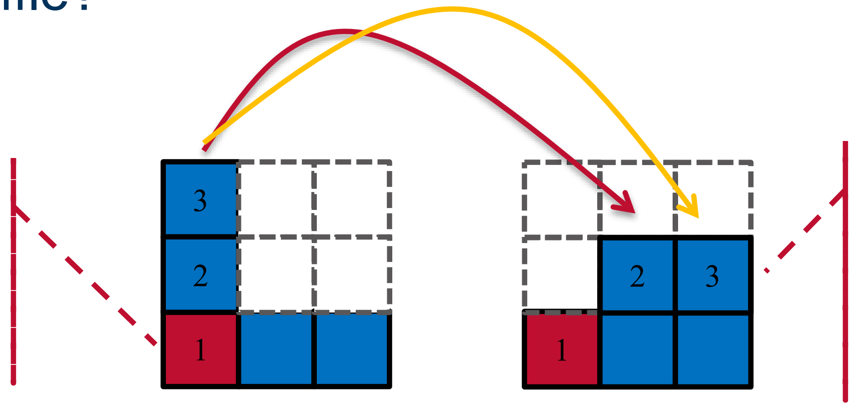
Pre-marshalling (or housekeeping) to prevent "reshuffles"

A major source of inefficiency (Choe et al., 2011)

Also called "rehandle", "restow", or "repositioning"

Research motivations

What is a reshuffle?



Numbers inside the containers indicate their priority orders

To reach container 1, 2 and 3 must be reshuffled. Both movements are non-productive

How does pre-marshalling work?

Reorder containers during off-peak hours to eliminate reshuffles during loading/retrieval in a yard bay

Why is pre-marshalling needed?

Scarcity of empty yard slots
Random container arrivals
Imprecise container information

(Kang et al., 2006; Lee and Chao, 2009; Choe et al., 2011).

Research motivations

Environmental sustainability in maritime shipping and port operations

Common practices

Speed reduction
Re-routing
Berth scheduling

(*Mansouri et al., 2015*)

Main research areas

Emission reduction
Eco-efficient operations
Climate change and regulation
Ship design and mobility
Carbon footprint case studies

(*Davarzani et al., 2016*)

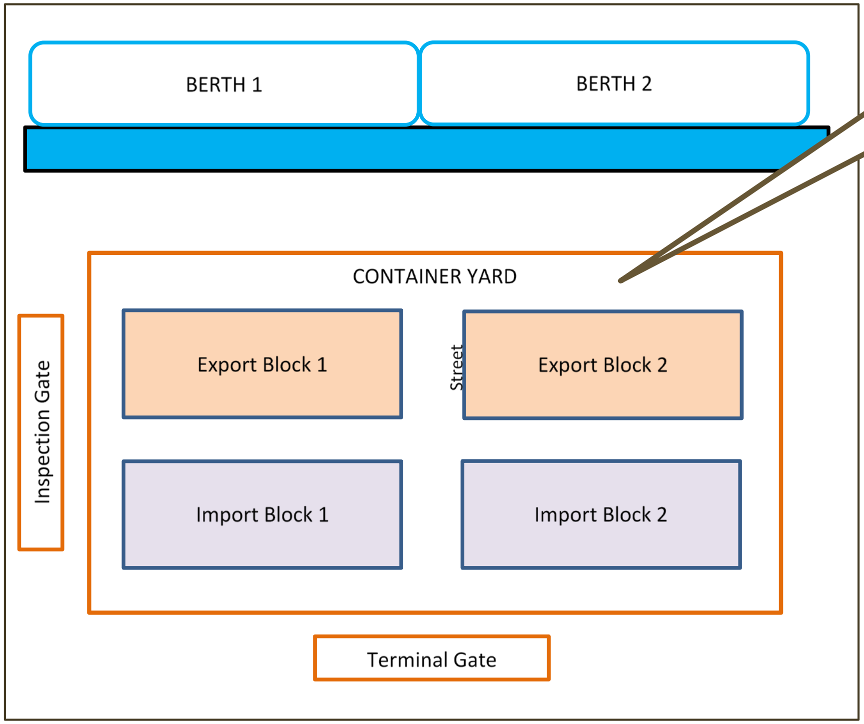
Regulatory developments

MARPOL Convention (IMO, 1973-1997)
ISO 14001 (1996, 2004, 2015)
Ecoports (ESPO, 1997, 2011)

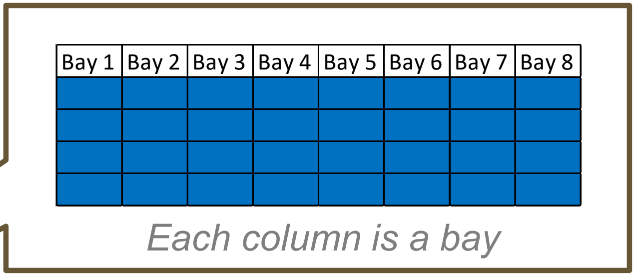
Problem definition

Common terminology

***Blocks** (or streets) are collections of container bays*

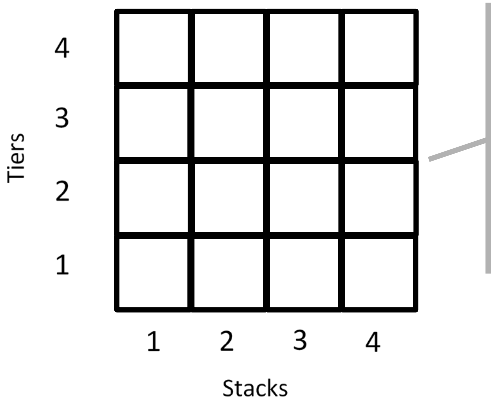


Container terminal layout



Each column is a bay

***Bay**: A rectangular configuration of container slots divided column-wise into stacks and row-wise into tiers.*



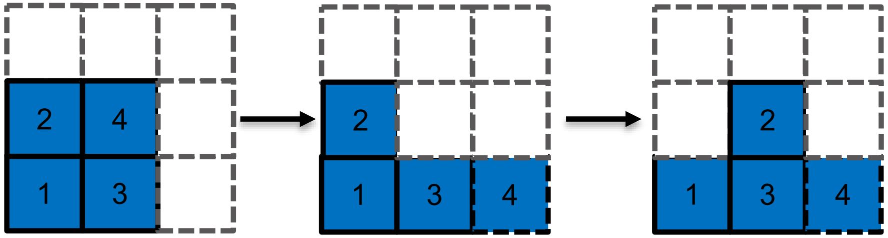
4 x 4 = 16
container
slots

Problem definition

A pre-marshalling example

An “unordered” bay configuration: 2 blocks 1, and 4 blocks 3

Move container 4 from stack 2 to stack 3



Initial bay configuration

1st move

2nd move

Move container 2 from stack 4 to stack 1

An “ordered” bay configuration: None of the containers are blocked by others.

Literature review

Container pre-marshalling problem: Minimize **the number of container movements** required to obtain an ordered bay

- Lee and Hsu, 2007: Multi-commodity flow formulation
- Lee and Chao, 2009: Neighbourhood search + integer programming
- Bortfeldt and Forster, 2012: Tree search heuristic
- Expósito-Izquierdo et al., 2012: A* heuristic, instance generator
- Rendl and Prandstetter, 2013: Constraint programming
- Jovanovic et al., 2017: Greedy heuristic
- Tierney et al., 2017: A* & IDA algorithms
- Tanaka and Tierney, 2018: Iterative deepening branch and bound
- Tierney et al., 2019: Branch and bound algorithm
- Parreño-Torres et al., 2019: New integer programming formulations
- Hottung et al., 2020: Deep learning heuristic tree search

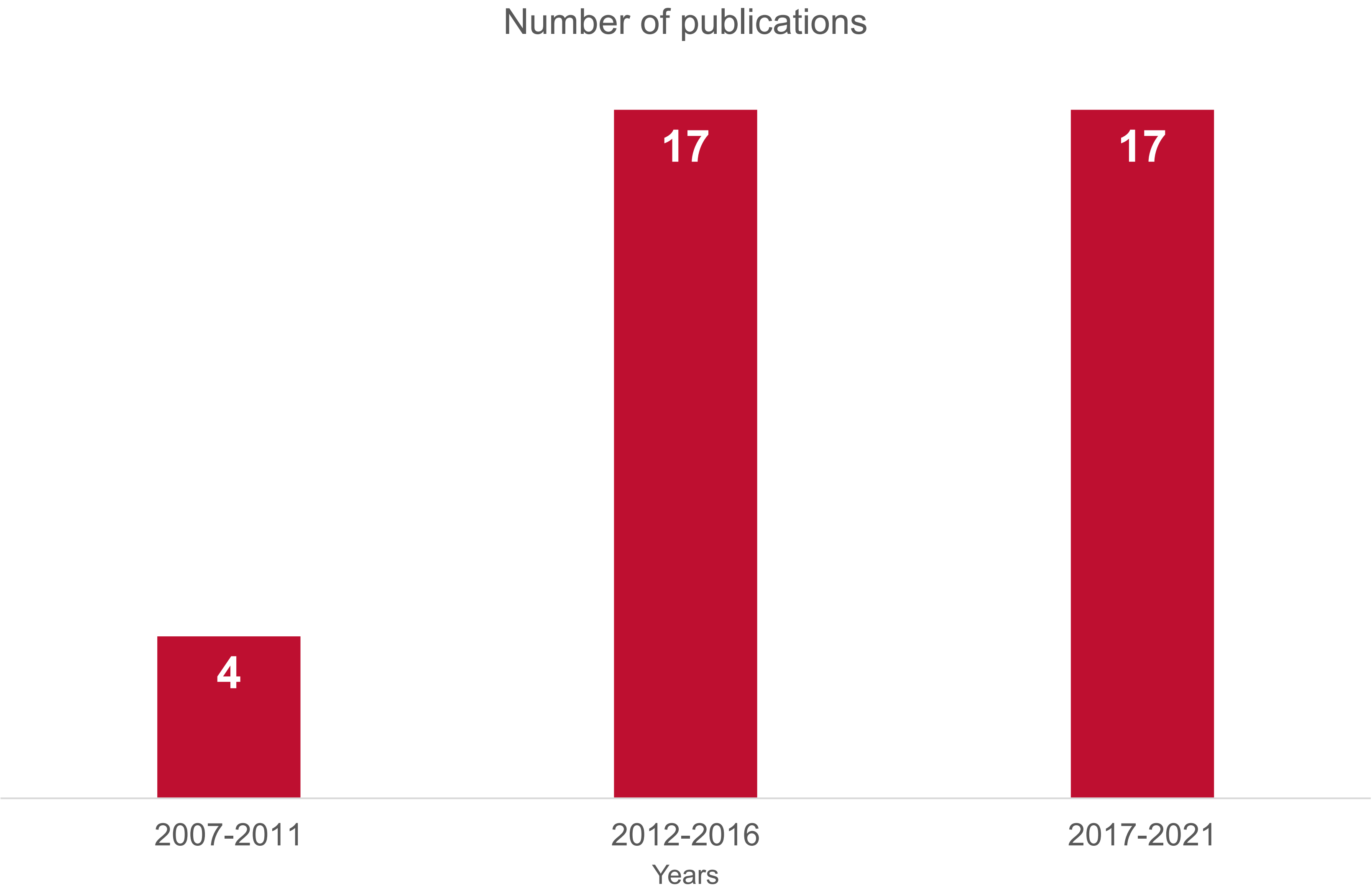
Literature review

Non-conventional problem definitions appear recently:

- Parreño-Torres et al., 2020: Minimize crane times in pre-marshalling problems
- Boge et al., 2020: Robust optimization for premarshalling with uncertain priority classes
- Zweers et al., 2020: Stochastic container relocation problem with constrained pre-processing

Literature review

13 July 2021



Problem definition

(Source: https://www.termavi.com/en/multimedia-2/)

Container pre-marshalling problem with sustainability considerations

For a given initial bay configuration and the (retrieval) priority order of the containers, determine the sequence of the container movements so as to minimize **the total energy consumption of the yard cranes** and **achieve an *ordered* bay.**

Problem definition

Assumptions:

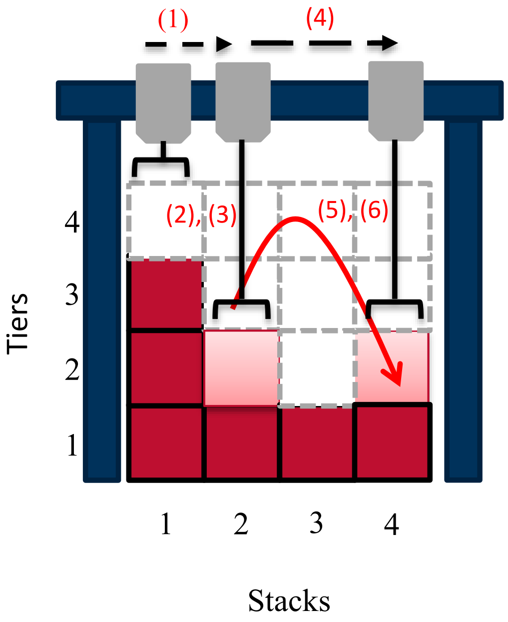
- All containers are assumed to be of the same size and dimensions (1 TEU).
- The priority order of the containers for retrieval is known in advance.
- Only one crane operates on the bay, and only a single container can be moved at a time.
- The number of containers in the bay does not change during the pre-marshalling operation.
- All stacks and tiers in the bay are identical.
- Each slot can contain at most one container.
- The unit idle and operational energy consumption of the cranes are known and constant for each container.

(*Lee and Hsu, 2007; Lee and Chao, 2009; Wang et al., 2015; 2017; Tierney et al., 2017; Tanaka and Tierney, 2018*)

Model formulation

- The proposed mixed integer programming model is formulated by partially adopting the classical pre-marshalling problem formulation proposed by Parreño-Torres et al. (2019).
- The crane energy consumption of a single container movement is calculated by considering six crane manoeuvres:

1. Movement of the crane's trolley from its previous position to the source stack s
2. Lowering of the spreader to the topmost container of stack s
3. Hoisting of the topmost container with the spreader
4. Movement of the crane's trolley from s to the target stack k
5. Lowering of the spreader to place the container on top of stack k
6. Hoisting of the spreader back to the trolley



Model formulation

Set	Explanation
$\mathcal{S}$	Set of stacks, $s, k, l = \{1, \dots, S\}$
$\mathcal{H}$	Set of tiers, $h, e = \{1, \dots, H\}$
$\mathcal{T}$	Set of time segments, $t = \{1, \dots, T\}$
$\mathcal{P}$	Set of container retrieval priorities, $p, r = \{1, \dots, P\}$

Parameter	Explanation
N_p	The number of containers in priority group p,
tfl_{sk}	The energy consumed for moving the trolley loaded with a container from stack s to k
tfu_{ls}	The energy consumed for moving the trolley unloaded from stack l to s
tfi_h	The energy consumed by keeping the trolley idle during the spreader's movement between trolley level and tier h
sfl_h	The energy consumed for lowering the spreader empty to tier h and hoisting a container to the trolley level
sfu_h	The energy consumed for lowering the spreader loaded with a container to tier h and hoisting it empty to the trolley level
sfi_{sk}	The energy consumed by keeping the spreader idle during the trolley's movement from stack s to k

Model formulation

Decision variables

Y_{shkept}	1 if a container of priority p is moved from stack s tier h to stack k tier e between the time segments t and $t+1$, 0 otherwise $\forall\, s \in \mathcal{S}, h \in \mathcal{H}, k \in \mathcal{S} \setminus \{s\}, e \in \mathcal{H}, p \in \mathcal{P}, t \in \mathcal{T} \setminus \{T\}$
X_{shpt}	1 if a container with priority p occupies stack s tier h at the beginning of time segment t, 0 otherwise $\forall\, s \in \mathcal{S}, h \in \mathcal{H}, p \in \mathcal{P}, t \in \mathcal{T}$
C_{lst}	1 if the trolley is moved from stack l to s for moving a container from stack s between the time segments t and $t+1$, 0 otherwise $\forall\, l \in \mathcal{S}, s \in \mathcal{S}\ \{l\}, t \in \mathcal{T} \setminus \{1, T\}$

Model formulation

$Minimise$

$$\sum_{l=1}^{S}\sum_{s=1}^{S}\sum_{t=2}^{T-1}(tfu_{ls} * C_{lst}) + \tag{1}$$

(1) Minimize the total energy consumption of the crane to perform all movements

$$\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{\substack{k=1\\k\neq s}}^{S}\sum_{e=1}^{H}\sum_{p=1}^{P}\sum_{t=1}^{T-1}\Big((tfl_{sk} + tfi_h + tfi_e + sfi_{sk} + sfl_h + sfu_e) * Y_{shkept}\Big)$$

$such\ that$

$$\sum_{s=1}^{S}\sum_{h=1}^{H} X_{shpt} = N_p \quad \forall\, p \in \mathcal{P}, t \in \mathcal{T} \tag{2}$$

(2) Assign a slot position to all containers at all time segments

$$\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{\substack{k=1\\k\neq s}}^{S}\sum_{e=1}^{H}\sum_{p=1}^{P} Y_{shkept} \leq 1 \quad \forall\, t \in \mathcal{T} \setminus \{T\} \tag{3}$$

(3) 1 movement per time segment

$$\sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{\substack{k=1\\k\neq s}}^{S}\sum_{e=1}^{H}\sum_{p=1}^{P} Y_{shkept+1} \leq \sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{\substack{k=1\\k\neq s}}^{S}\sum_{e=1}^{H}\sum_{p=1}^{P} Y_{shkept} \quad \forall\, t \in \mathcal{T} \setminus \{T-1, T\} \tag{4}$$

(4) Perform the movements at earliest time segments

Model formulation

$$\sum_{p=1}^{P} X_{s1pt} \leq 1 \quad \forall\, s \in \mathcal{S}, t \in \mathcal{T} \setminus \{1\} \tag{5}$$

(5)-(6) Each tier at most 1 container

$$\sum_{p=1}^{P} X_{sh+1pt} \leq \sum_{p=1}^{P} X_{shpt} \quad \forall\, s \in \mathcal{S}, h \in \mathcal{H} \setminus \{H\}, t \in \mathcal{T} \setminus \{1, T\} \tag{6}$$

(7) Only move the topmost container at each stack

$$X_{shpt} + \sum_{r=1}^{P} X_{sh+1rt} \leq 1 + X_{shpt+1} \quad \forall\, s \in \mathcal{S}, h \in \mathcal{H} \setminus \{H\}, p \in \mathcal{P}, t \in \mathcal{T} \setminus \{T\} \tag{7}$$

$$\sum_{\substack{s=1 \\ s \neq k}}^{S} \sum_{h=1}^{H} \sum_{e=1}^{H} Y_{shkept} + \sum_{\substack{s=1 \\ s \neq k}}^{S} \sum_{h=1}^{H} \sum_{e=1}^{H} Y_{keshpt+1} \leq 1 \quad \forall\, k \in \mathcal{S}, p \in \mathcal{P}, t \in \mathcal{T} \tag{8}$$

(8) Prevent transitive moves (Tierney et al., 2017)

$$\sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} Y_{shkept} + \sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} Y_{keshpt+1} \leq 1 \quad \forall\, s \in \mathcal{S}, h \in \mathcal{H}, p \in \mathcal{P}, t \in \mathcal{T} \setminus \{T-1, T\} \tag{9}$$

(9) Prevent symmetrical moves (Tanaka and Tierney, 2018)

$$X_{shpt} + \sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} Y_{keshpt} = X_{shpt+1} + \sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} Y_{shkept} \quad \forall\, s \in \mathcal{S}, h \in \mathcal{H}, p \in \mathcal{P}, t \in \mathcal{T} \setminus \{T\} \tag{10}$$

(10) Slot occupation constraint

Model formulation

$$\sum_{r=p}^{P} X_{sh+1rT} \le \sum_{r=p}^{P} X_{shrT} \quad \forall\ s \in \mathcal{S}, h \in \mathcal{H} \setminus \{H\}, p \in \mathcal{P} \tag{11}$$

(11) The bay is ordered at T

$$C_{lst} \le \sum_{h=1}^{H} \sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} \sum_{p=1}^{P} Y_{shkept} \quad \forall\, l \in \mathcal{S}, s \in \mathcal{S}, t \in \mathcal{T} \setminus \{1, T\} \tag{12}$$

$$C_{lst} \le \sum_{\substack{k=1 \\ k \neq l}}^{S} \sum_{e=1}^{H} \sum_{h=1}^{H} \sum_{p=1}^{P} Y_{kelhpt-1} \quad \forall\, l \in \mathcal{S}, s \in \mathcal{S}, t \in \mathcal{T} \setminus \{1, T\} \tag{13}$$

(12)-(14) C_{lst} is 1 if and only if the target stack of the movement during t−1 was l and the source stack of the movement during t is s

$$\sum_{\substack{k=1 \\ k \neq l}}^{S} \sum_{e=1}^{H} \sum_{h=1}^{H} \sum_{p=1}^{P} Y_{kelhpt-1} + \sum_{h=1}^{H} \sum_{\substack{k=1 \\ k \neq s}}^{S} \sum_{e=1}^{H} \sum_{p=1}^{P} Y_{shkept} \le C_{lst} + 1 \quad \forall\, l \in \mathcal{S}, s \in \mathcal{S}, t \in \mathcal{T} \setminus \{1, T\} \tag{14}$$

$$Y_{shkept}, C_{lst} \in \mathbb{R}^{+}, X_{shpt} \in \{0,1\} \quad \forall\, s, k, l, e, h, p, t \tag{15}$$

(15) Integrality and nonnegativity constraints

Solution heuristic development

- An A* algorithm-based solution heuristic is being developed.
- A* algorithm is a well-known pathfinding algorithm and was proposed to solve the conventional pre-marshalling problem (Exposito-Izquierdo et al., 2012; Tierney et al., 2017)
- In a graph of **nodes**, iteratively construct the shortest path between a **starting location** and a **destination** using a function on the sum of **exact and estimated costs** (distances):

$$f(n) = g(n) + h(n)$$

The exact cost from start to node *n*

The estimated cost from node *n* to destination

Solution heuristic development

- In the proposed solution method, the energy consumption function is incorporated into the A* algorithm, and path selection is made based on the realized and estimated energy consumptions.
- Assume initial bay configuration as the starting location and any ordered bay configuration as the destination.
- Each intermediate bay configuration refers to the nodes visited along the path between the starting location and destination.
- The algorithm favours the paths which have the lowest total energy consumption.
- (Under development): To intensify the search in promising paths, hybridize the A* algorithm with an evolutionary heuristic.
  - Select “*m*” elite paths with minimum total energy consumption
  - Generate random move sequences from each elite path.
  - Apply evolutionary mechanisms to optimize the move sequences
  - Stop if a sequence yields an ordered bay.

Computational experiments

Experiment instances:

	Stacks	Tiers	Containers
Lee and Hsu (2007)	6	4	14
Expósito-Izquierdo et al. (2012)	4	4	8 /12 / 16
	7	4	7 / 14 /28
	10	4	10 / 20 / 40
This paper	6	4	10
Use case Spanish terminal	6	4	Various

Computational experiments

13 July 2021

Preliminary observations

Container movements and energy consumption do not conflict with each other according to the observations

4-6% energy reduction with the proposed objective function

The solution heuristic can find good solutions for instances with low bay occupation ratio (=containers/total bay capacity) in a reasonable computation time.

The heuristic slows down with difficult instances (i.e. high bay occupation ratio and/or a bay with more stacks/tiers) due to the memory issues.

Computational experiments

PortForward project funded under EU Horizon 2020 program (2018-2021)

Green Yard Scheduler: A DSS to optimize container yard operations

Case Study

Design and develop a Housekeeping optimization module

Use case: A Spanish container terminal

Conclusions

- Container pre-marshalling problem with sustainability considerations is introduced.
- An integer programming model formulation is presented and a solution heuristic is discussed.
- Preliminary experiment results are discussed.

Future research:

- Complete the hybridization of A* algorithm with evolutionary heuristic to find good solution for difficult pre-marshalling problem instances.
- Expand the research to intra-bay pre-marshalling movements.

Acknowledgements: *This project receives funding in the European Commission's Horizon 2020 Research Program under Grant Agreement Number 769267*

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Thank you for your attention!
Questions, comments?

13 July 2021

Contact Details

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Dr Cihan Bütün

Address: Brunel University London,
Uxbridge, Middlesex UB8 3PH,
United Kingdom

Department: Brunel Business School

Email: cihan.butun@brunel.ac.uk

[Dr Cihan Butun | Introduction | Brunel University London]()

https://www.linkedin.com/in/cihanbutun/