

---

## **Performance assessment and improvement of yard crane rehandling strategies for improving port drayage operations**

---

**Nathan Huynh\***

Department of Civil and Environmental Engineering,  
University of South Carolina,  
300 Main St. Columbia, SC 29208, USA  
E-mail: huynhn@cec.sc.edu  
\*Corresponding author

**Jose M. Vidal**

Department of Computer Science and Engineering,  
Swearingen Engineering Center,  
University of South Carolina,  
Columbia, SC 29208, USA  
E-mail: jmvidal@gmail.com

**Narges Kaveshgar and Omor Sharif**

Department of Civil and Environmental Engineering,  
University of South Carolina,  
300 Main St. Columbia, SC 29208, USA  
E-mail: nkaveshgar@gmail.com    E-mail: omor.sharif@gmail.com

**Abstract:** Seaport terminals recognise the need to change current practices in order to improve regional air quality while enhancing their terminals' competitiveness. One area that terminals can do better at is to improve their yard crane operations and in turn reduce the trucks in-terminal delay. This study examines various container rehandling strategies by the yard cranes with the goal of improving the time it takes for a drayage truck to pick up an import container and hence reducing the time of engine idling and the stop-and-go lugging. Simulation results highlight the benefit of having truck arrival information, and they indicate that this study's proposed rehandling methods, which take advantage of truck arrival information, perform well compared to other methods. Also, the proposed backfilling method appears to be quite effective in reducing truck wait time.

**Keywords:** seaport container terminals; simulation; yard crane service strategies improvement; terminal and port drayage efficiency; environmental stewardship.

**Reference** to this paper should be made as follows: Huynh, N., Vidal, J.M., Kaveshgar, N. and Sharif, O. (2012) 'Performance assessment and improvement of yard crane rehandling strategies for improving port drayage operations', *Int. J. Six Sigma and Competitive Advantage*, Vol. 7, No. 1, pp.41–61.

**Biographical notes:** Nathan Huynh is an Assistant Professor in the Department of Civil and Environmental Engineering at the University of South Carolina. He obtained his MS and PhD in Civil Engineering with specialisation in transportation engineering from the University of Texas at Austin. His research focuses on improving processes in the areas of logistics and healthcare. He has a special interest in utilising technology, optimisation, and simulation techniques to bridge the gap between theoretical research and applications.

Jose M. Vidal is an Associate Professor in the Department of Computer Science and Engineering at the University of South Carolina. He obtained his MS in Computer Science from Rensselaer Polytechnic Institute and PhD in Computer Science and Engineering from the University of Michigan. His research interests include multi-agent systems, agent-based modelling, web applications, algorithmic game theory, negotiation networks, and distributed algorithms.

Narges Kaveshgar is currently a PhD student in the Department of Civil and Environmental Engineering at the University of South Carolina. She obtained her MS in Civil Engineering (transportation) from Islamic Azad University. Her research interests include applications of operations research and optimisation techniques to improve port operations.

Omor Sharif is currently a PhD student in the Department of Civil and Environmental Engineering at the University of South Carolina. He obtained his MS in Civil Engineering (transportation) from the University of South Carolina. His research interests include container transportation and logistics, marine container terminal planning and operational management, development of decision support systems, mathematical optimisation and agent-based simulation.

---

## 1 Introduction

Port drayage activities play an important role in supply chain and logistics. Despite the relatively short distance of the truck movement compared to the rail or barge haul, drayage accounts for a large percentage, between 25% and 40%, of origin to destination expenses (Macharis and Bontekoning, 2004). High drayage costs seriously affect the profitability of an intermodal service which in turn could impede the advance of intermodal freight transportation. Another important reason to improve drayage operations is to reduce time of engine idling and the stop-and-go lugging; drayage trucks are diesel-fuelled, heavy-duty trucks that transport containers, bulk, and break-bulk goods to and from ports and intermodal rail yards (California EPA, 2009). Reducing the drayage trucks in-terminal dwell time is equivalent to reducing local and regional particulate matter (PM 2.5), nitrogen oxides (NO<sub>x</sub>), and greenhouse gas (GHG) emissions. PM 2.5 emissions from diesel engines are recognised by the Environmental Protection Agency (EPA) as a serious health issue. Recognising the serious negative health effects of GHG emissions, President Obama has called for a reduction in the USA by 17% by 2020 at the United Nations climate summit in Denmark in December 2009 (msnbc.com news service reports, 2009).

The seaport container terminals have long been identified as bottlenecks and sources of delay for port drayage. The time drayage trucks spent in the queue at the entry gate, container yard, and exit gate are often exceedingly long during peak times at busy terminals. High truck turn time is the result of demand exceeding supply. Truck turn time refers to the time it takes a drayage truck to complete a transaction such as picking up an import container or dropping off an export container. Specifically, it is the difference between the truck's exit time and the truck's entrance time. It is a measure of a terminal's efficiency in receiving and delivering containers. For terminals that stack their containers, yard cranes are the most commonly used equipment to transfer containers in and out of the stacks. The job of the yard cranes includes transferring containers from drayage trucks from the community to the stacks (i.e., export container) and vice versa (i.e., import container), transferring containers from an internal transfer vehicle to the stacks (i.e., import container) and vice-versa (i.e., export container), and transferring containers in and out of the stacks in support of warehouse, rail, and inspection operations. On any given day, a portion of the yard cranes are assigned to support vessel import discharge and export loading operations and the remainder is assigned to support the road export drop-off and import pick-up operations. Given a limited number of yard cranes available, the service strategy and rehandling strategy followed by the cranes in servicing the drayage trucks has significant effects on the wait time of trucks.

A truck's wait time in the container yard is dependent on three factors:

- 1 the ratio of trucks to yard cranes
- 2 the yard crane service strategy
- 3 the yard crane rehandling strategy.

The ratio of trucks to yard cranes can be reduced by purchasing more yard cranes; however, the high initial investment, plus expensive maintenance and operating costs of these cranes often prohibit terminals from pursuing this option. Improving the yard crane service strategy and rehandling strategy is a more practical and less costly alternative for terminal operators. Our previous research show that the *distance-based* service strategy is one of the most effective strategies among those we evaluated and one that closely mimics actual practice at the Port of Houston and Port of Charleston. Building on our previous work, this study focuses on item 3: yard crane rehandling strategy. Specifically, this paper seeks to assess various rehandling strategies to improve drayage operations. The strategies to be compared consist of industry practices, those employed by others in past work, and new strategies proposed by this study. An agent-based simulation model is used to investigate the effectiveness of different rehandling strategies under a variety of operational scenarios.

The remainder of this paper is organised as follows: Section 2 provides a brief review of related work, followed by a general description of the problem being addressed in this paper (Section 3). Section 4 presents the employed methodology, which includes discussions about the agent-based simulation model and utility functions as well as the various rehandling strategies. Section 5 provides implementation details concerning the model. Section 6 discusses the validation of the model. Section 7 presents and analyses the simulation results. Lastly, Section 8 provides concluding remarks, including practical implications as a result of the study's findings.

## 2 Prior research

There is a vast amount of literature in the area of marine container terminal modelling. With container terminal operations becoming more and more important, an increasingly rapid number of publications on container terminals have appeared in the literature. A comprehensive review of previous work is beyond the scope of this paper. For an up-to-date review, readers are referred to the works by a team of researchers from Hamburg, Germany who compiled and summarised over 300 literature sources that address container terminal operations (Stahlbock and Voß, 2008; Steenken et al., 2004). The following review is limited to published works that pertain to yard cranes scheduling at marine container terminals, agent-based modelling in the context of marine terminals, and container rehandling.

Much of the research directly related to yard cranes has been carried out using operations research (OR)-based mathematical programming models such as integer programmes or mixed integer programmes. As such, these studies seek to optimise the work flow of cranes for a given set of jobs with different ready times in the yard. The ‘jobs’ considered vary from study to study; they could be either drayage trucks, or other yard handling equipment such as internal transfer vehicles. Given that the scheduling problem is NP-complete, these studies propose algorithms or heuristics to solve real-world, large-scale problems in a reasonable amount of time, including dynamic programming-based heuristic (Ng, 2005), branch and bound algorithm (Ng and Mak, 2005), Lagrangean relaxation (Zhang et al., 2002), and simulated annealing (Lee et al., 2007).

Multi-agent systems (MAS) has become an important field within artificial intelligence research, and it has been successfully applied to applications such as control processes, mobile robots, air traffic management, and intelligent information retrieval. Far fewer applications are found in the areas of freight and intermodal transportation, in particular, seaport container terminals. The application of MAS to solving terminal related problems include the evaluation of automated guided vehicle systems (Henesey, 2009a), evaluation of operational policies in the transshipment of containers (Henesey, 2009b), quay crane scheduling (Thurston and Hu, 2002), container allocation to yard (Rebollo, 2001), and resource allocation (Gambardella, 1998).

In the area of container rehandling, a few studies have proposed methods to estimate the expected number of rehandles. McDowell et al. (1985) proposed a recursive method for estimating the rehandles and developed a computer programme to perform the calculations. Watanabe (1991) proposed some practical equations to address the same problem. Kim (1997) extended Watanabe’s work by developing more accurate equations. A more general problem of handling and space cost is addressed recently by Park and Kim (2010). Castilho and Daganzo (1993) provided a set of equations to estimate rehandles in their work that addressed handling strategies for import containers. It is noted that none of these works allows for *ad hoc* rehandling strategies, and they all require containers in a bay to have equal probability of being selected.

Container rehandling has also been studied in the context of container storage and stacking logistics. Kim et al. (2000) proposed a dynamic programming model to determine the optimal storage location for incoming export containers such that the number of rehandles is minimal during the vessel loading operation. Kim and Hong (2006) investigated methods to minimise the total number of container rehandling during

the pickup operation for the entire container yard. Similarly, Lee and Lee (2010) proposed a three-phase heuristic to determine an optimal work plan for a crane to retrieve all the containers from a given yard with the goal of minimising the number of container movements and cranes' working time.

The study by Kim and Hong (2006) and Zhao and Goodchild (2010) are the two most closely related studies to our work described here. However, there are unique differences between our work and theirs. Unlike the Kim and Hong's work where they provided an analytical approach to estimating the expected number of additional relocations, this study evaluates the effectiveness of a rehandling strategy by measuring the actual effect it has on the truck wait time. In Zhao and Goodchild's work, they introduced a revised difference heuristic (RDH) for rehandling containers to avoid future rehandling. In the same spirit, in this study we introduced several new rehandling strategies which will then be comparatively assessed against the RDH and several industry practices.

To our knowledge, no agent-based work has examined yard crane service strategies and/or rehandling strategies and their impact on drayage operations, as done in this study. The agent-based feature differentiates this study from previous works. Specifically, each agent (i.e., crane operator) makes decisions based on his utility-maximising behaviour and not a deterministic or prescribed ad-hoc rule. Thus, the resulting crane work flow is not centrally controlled by some optimal schedule; rather it stems from the individual decisions made by the crane operators so it is a better model of port operations where crane operators are allowed to make their own decisions. Also, the practice of backfilling has never been examined in past work. In this study, the effect of backfilling in conjunction with various rehandling strategies is explored.

### **3 Background and problem description**

A drayage driver arriving to pick up a loaded import container may encounter one of three types of terminal

- 1 wheeled carrier
- 2 stacked carrier
- 3 stacked and straddle carrier.

The yard crane scheduling problem addressed in this study involves stacked terminals, and the study is focused on import pickup operations. At stacked terminals, the containers are stacked on top of one another in separate yard blocks. Each yard block has about 80 20-foot bays, each bay has six rows, and each row has four tiers (see Figure 1 for an illustration). A yard block is used for storing import containers, export containers, or both. Import containers are typically stored in the available blocks designated for imports and where it is most convenient for the stevedores to perform vessel operations. As import containers are discharged from a vessel, they are stacked in the allocated space without any segregation. Typically, they are high-piled on top of one another from bay to bay. In this manner, no effort is made by the terminal operator to stack the import containers in a way to expedite the import pickup operations. There are two reasons for this:

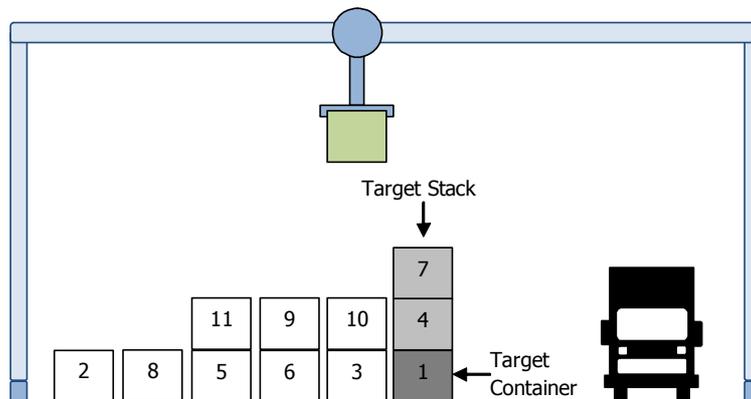
- 1 it is necessary to turn the vessel around as quickly as possible and the high-pile method is the fastest way to unload import containers
- 2 the terminal operator does not know in advance the order of trucks that will arrive to pick up import containers.

**Figure 1** Illustration of bay, row, and tier in a yard block (see online version for colours)



When the drayage truck arrives at the container terminal, it must first receive clearance to enter the container yard. The clearance procedure involves terminal personnel making administrative, safety, and security checks on the driver, truck, and chassis. Once the clearance procedure is completed, the driver will receive a pickup ticket with instructions on where to go in the yard to pick up the import container. The driver will then proceed to the specified yard location and wait for the yard crane to come to load the import container onto his chassis. When the yard crane arrives at the bay where the truck is waiting, the crane operator must locate the requested container and often he must rehandle other containers sitting on top of the target container. The driver can proceed to the exit gate after the container is loaded onto his truck. The driver will undergo a similar clearance procedure at the exit gate, with the addition of container inspection, if applicable; some terminals do not require this. The import pickup process ends when the driver receives an equipment interchange report (EIR), and exits the terminal.

**Figure 2** Illustration of the container rehandling problem (see online version for colours)



The container rehandling problem addressed in this study deals with the strategy the cranes employ in rehandling the containers sitting on top of the target container (i.e., the container to be delivered to the truck). Consider the scenario illustrated in Figure 2 where the target container is the container with ID #1. In order to deliver container #1, the yard crane must first rehandle container #7 and then container #4. The stacks where containers #7 and #4 are placed into are thus affected. For example, if container #7 is placed onto the stack with container #2, then that means container #7 would then have to be rehandled first if the target container of the next truck is container #2. It is evident that the rehandling strategy could have a significant impact on the overall wait time of the trucks. Thus, the objective of the container rehandling problem is to find the best location for relocating containers to minimise the total truck wait time.

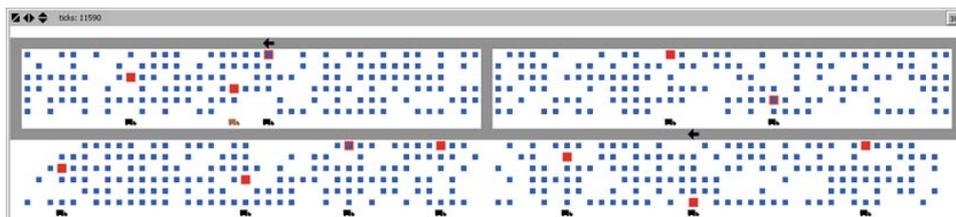
## 4 Methodology

As mentioned, this study builds on our previously developed agent-based model and findings regarding the effectiveness of the distance-based strategy. This section first describes how we model crane operators as utility-maximising agents and presents information about our simulation model. This is followed by a description of the various rehandling strategies assessed in this study.

### 4.1 Simulation model

To suitably capture the decision making criteria of the crane operators, this study models crane operators as utility-maximising agents that operate autonomously and can constantly re-evaluate their utility functions. More formally, we say that there is a set  $C$  of cranes so that each crane  $c \in C$  has a utility function  $u_c(t)$  over all trucks  $t \in T$  in the yard. Each of these utility functions weighs different aspects of the move. One of those factors is the shortest path between the crane and the truck. As can be seen in Figure 3, there are a number of different paths that a crane can take to get to a container, some much longer than others; note that yard cranes are represented by arrows and the grey areas denote the cranes travel paths. Thus, we let  $PATH(c, t)$  be the shortest path between crane  $c$  and truck  $t$ . Similarly, we denote  $DISTANCE(p)$  to be the distance of a path  $p$ ,  $HAS - TURN?(p)$  to be a Boolean function that returns 1 if path  $p$  requires the crane to turn, that is, move from one of the top two blocks to one of the bottom two blocks or vice-versa, and  $OTHER - CRANE?(p, c)$  to be a Boolean function that returns 1 if  $p$  passes over some cranes other than  $c$ .

**Figure 3** Screenshot of agent-based model of yard cranes at a seaport container terminal (see online version for colours)



In our model, each crane  $c$  has a current goal  $g_c$  which can be either empty ( $\emptyset$ ), contain a truck  $t$  which means that the crane's current goal is to go to the location of truck  $t$ , or it can have the value *deliver-container* which means the crane is currently at the truck's position and is in the process of loading a container from the stack onto the truck. To capture a crane operator's tendency to commit or not commit to a truck, we introduce a decommitment-penalty which can be set to 0 to model a crane operator's completely opportunistic behaviour or to some larger value to model an operator who is more committed to his current goal. Specifically, if  $g_c = (\emptyset)$  or  $g_c = t$  for some  $t$ , then the crane updates its goal at every time increment by first determining the optimal truck to service ( $t^*$ ) and then switching to truck  $t^*$  only if the utility of truck  $t^*$  is higher than the utility of the current goal plus the decommitment-penalty. This behaviour can be stated as follows.

$$t^* = \arg_{t \in T} \max u_c(t) \quad (1)$$

$$g_c = \begin{cases} t^*, & \text{if } u_c(t^*) > u_c(g_c) + \text{decommitment-penalty} \\ g_c, & \text{otherwise} \end{cases} \quad (2)$$

where  $u_c(\emptyset) = 0$ .

In this study, we use the distance-based utility function that capture the essence of how crane operators make their decisions as observed at the Port of Houston and Port of Charleston. The distance-based utility function captures the effective distance between the crane and a truck, giving higher priority to trucks that are closer to the crane. This distance is mostly just the path length between the crane and the truck, but also includes elements that consider the need for making a turn (as these take a longer time), the fact that there is another crane in the path (thus the path is blocked), whether or not the crane needs to change direction, and whether this crane is indeed the closest one to the truck. The last term provides the cranes with as light implicit form of coordination. More formally, we define this utility as

$$\begin{aligned} u_c^{\text{distance}}(t) = & -\text{DISTANCE}(\text{PATH}(c, t)) - \\ & p_1 \cdot \text{OTHER} - \text{CRANE}?(\text{PATH}(c, t)) - \\ & p_2 \cdot \text{HAS} - \text{TURN}?(\text{PATH}(c, t)) - \\ & p_3 \cdot \text{CHANGE} - \text{HEADING}?(\text{PATH}(c, t)) - \\ & p_4 \cdot \text{NOT} - \text{CLOSEST}?(c, t) \end{aligned} \quad (3)$$

where  $p_1, \dots, p_4$  are fixed penalty constants. Their values are set to be high enough such that a crane will never choose a truck for which any one of the terms are true (i.e., there is another crane on its path, or the crane must take a turn, or it must change its heading, or there is another crane closer to the truck). Note that the distance has a negative sign because the longer a crane has to travel the less utility it receives from that truck.  $\text{CHANGE} - \text{HEADING}?(p)$  is a Boolean function which returns 1 if the crane needs to change its current heading in order to follow path  $p$ , and  $\text{NOT} - \text{CLOSEST}?(c, t)$  is a Boolean function which returns 1 if crane  $c$  is not the one currently closest to truck  $t$  and 0 otherwise.

In modelling the yard crane gantry speed and handling times, empirical data are used. A typical yard crane can gantry (i.e., traverse along the yard block) at a speed of 135 meter per minute (<http://www.Kone.com>). Thus, it takes a crane about six seconds to

gantry from one 40-foot bay to the next. As mentioned previously, a truck's wait time is a combination of the time it takes a crane to arrive at the bay where the truck is parked and the time it takes the crane to perform both rehandling and delivery moves. The steps involved in performing a rehandle are as follows. These steps are repeated for every container that is sitting on top of the target container.

- 1 position spreader bar on top of container to be rehandled
- 2 lower the spreader bar
- 3 lock the spreader bar to the container
- 4 hoist the container
- 5 trolley to the desired stack
- 6 lower the container
- 7 unlock the spreader bar from the container
- 8 bring the spreader bar back to its normal position.

The steps involved in performing a delivery move are similar to a rehandle move. The key difference is in step 5 where instead of setting a container onto a stack, the crane operator sets the container onto the truck, which could take much longer time if the truck is not properly positioned. If the target container is at the bottom of a stack that is four high, then a crane will need to perform three rehandling moves and one delivery move. Data gathered previously by the authors show that the average rehandling time to be about 40 seconds and the delivery time to be about 87 seconds.

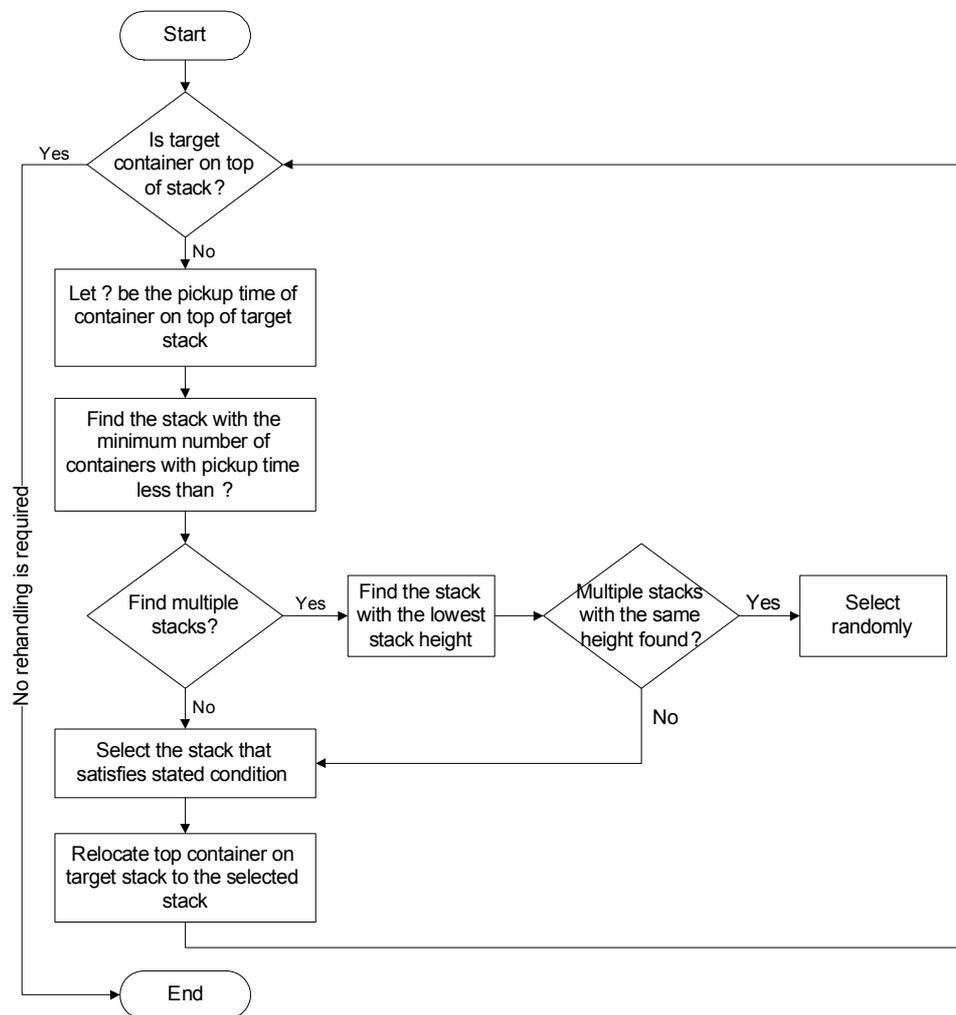
#### 4.2 Rehandling strategies

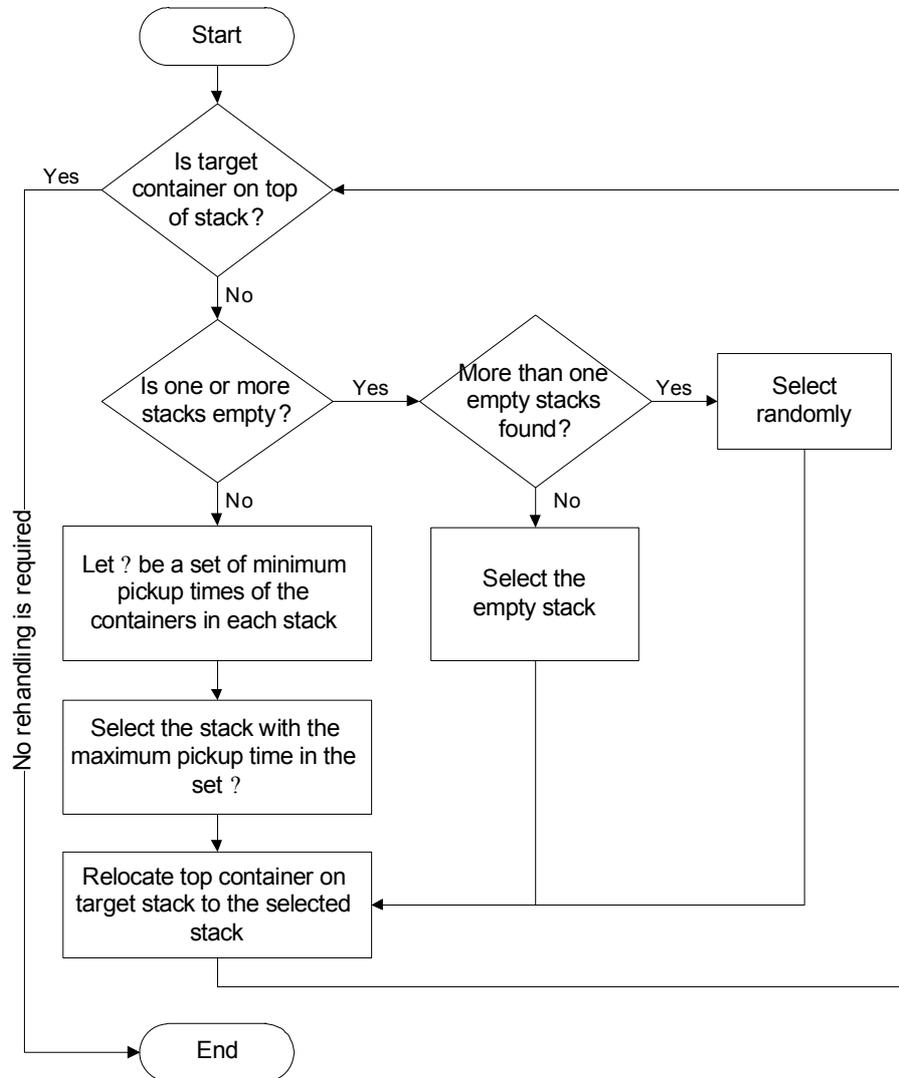
This study introduces two new rehandling strategies. Both strategies assume that the order of truck arrivals is known in advance as well as the pickup times of the associated containers. The container pickup time is the time when the truck is expected to be at the terminal to pick up the container. It is noted that trucks will not be served on a first-come first-serve basis because the sequence of trucks to be served are made independently by each crane agent based on the distance-based utility [equation (3)]. The first proposed strategy is named *least affected stack*. This strategy would search for a stack with the minimum number of containers with pickup times less than the container that has to be rehandled. In case of a tie it would select the lowest stack and if there is more than one stack with this condition it would choose one randomly. The second proposed strategy is named *max-min pickup time*. This strategy would first search for empty stacks and if there are more than one stack that satisfies this condition it would choose one randomly. If there are no empty stacks, it would find the minimum pickup time of the containers in each stack then choose the stack that has the maximum of minimum pickup times. Figures 4 and 5 provide additional details concerning the proposed strategies.

To assess the performance of the proposed strategies, they are compared against the *RDH* proposed by Zhao and Goodchild (see Figure 6). Similar to our proposed strategies, their strategy seeks to check various alternative locations to place there handled container to minimise additional future relocations, but as shown in Figure 6 their strategy requires more information and checking and is less intuitive. Additionally, two common industry

practices are used as benchmarks. The first one is named ‘lowest and closest to current stack’. This is a commonly used strategy where the crane operator simply looks to place the rehandled container in the lowest stack. If there is more than one stack with equal heights, he would choose the stack that is the closest to the stack of the rehandled container. The other real world strategy is named ‘lowest and farthest from truck’. This strategy is implemented at the Port of Houston to minimise the chances of the crane operators accidentally knocking nearby containers onto the trucks. Like the ‘lowest and closest to current stack’ strategy, the operator first looks for the lowest stack. If there is more than one stack with equal heights, he would choose the stack that is furthest away from the truck lane.

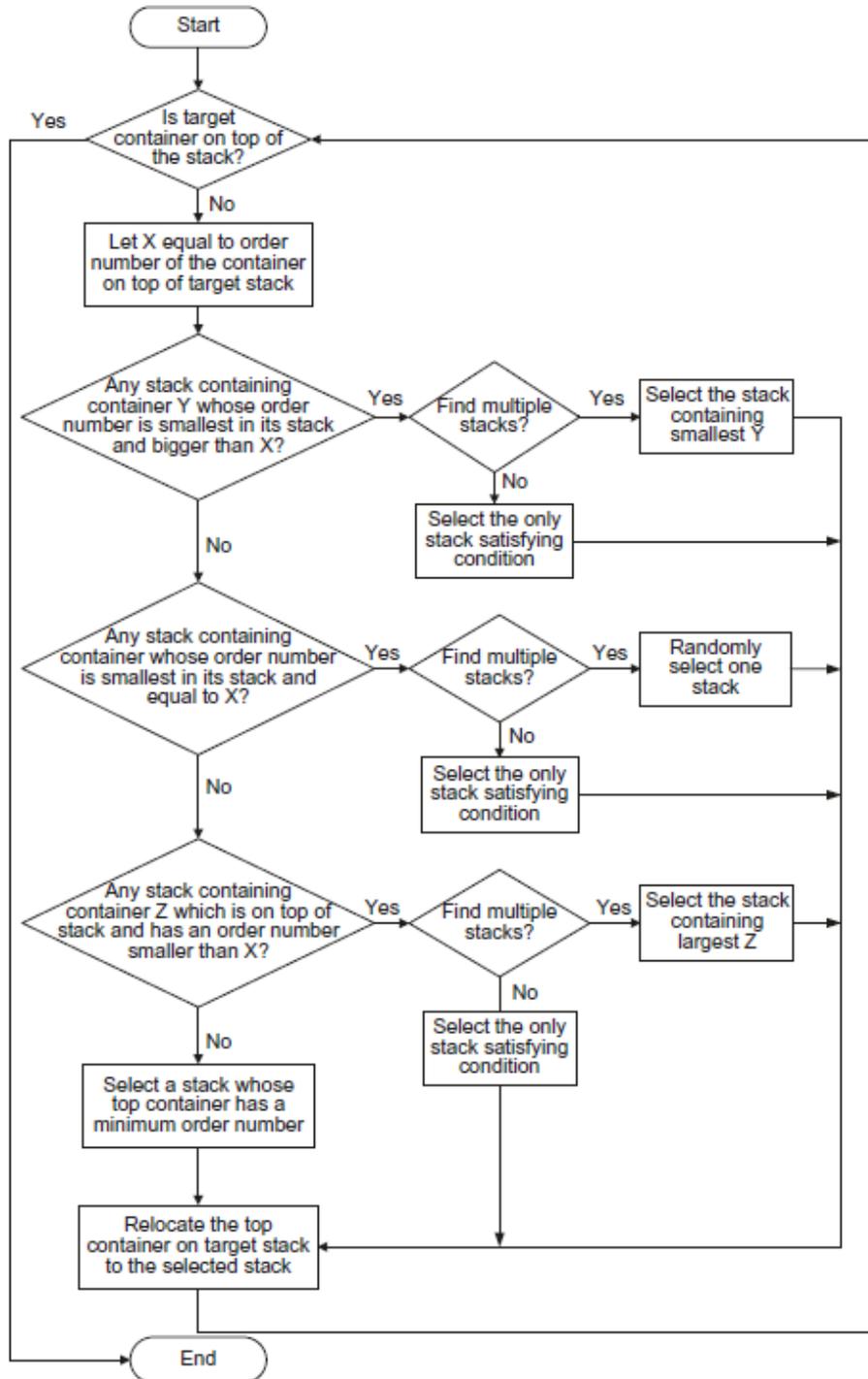
**Figure 4** Flow chart of least affected stack strategy



**Figure 5** Flow chart of max-min pickup time strategy

While not a rehandling strategy *per se*, a practice sometimes done at terminals is 'backfilling'. That is, once the target container is delivered to the truck, the containers that were rehandled are backfilled into the empty stack. This practice is done to avoid creating chimney stacks and/or uneven stack heights. The effect of such a practice is explored in this study.

Figure 6 Flow chart of RDH



Source: Zhao and Goodchild (2010)

To illustrate how these five strategies work, consider the stack configuration shown in Figure 2. Suppose we wish to deliver container 1 to the truck. In this case, first container 7 and then container 4 must be rehandled. The following shows where containers 7 and 4 will be placed by each strategy.

- 1 lowest and farthest from truck
  - Step one: set container 7 on top of container 2.
  - Step two: set container 4 on top of container 8.
- 2 lowest and closest to current stack
  - Step one: set container 7 on top of container 8.
  - Step two: set container 4 on top of container 2.
- 3 RDH
  - Step one:  $X=7$ ,  $Y=8$ , set container 7 on top of container 8.
  - Step two:  $X=4$ ,  $Y=5, 6$ , and  $7$ , set container 4 on top of container 11.
- 4 least affected stack
  - Step one:  $\theta=7$ , set container 7 on top of container 8.
  - Step two:  $\theta=4$ , set container 4 on top of container 7 or 11 or 9.
- 5 max-min pickup time
  - Step one:  $\lambda = \{2, 8, 5, 6, 3\}$  thus maximum member of  $\lambda = 8$ . Set container 7 on top of container 8.
  - Step two:  $\lambda = \{2, 7, 5, 6, 3\}$  thus maximum member of  $\lambda = 7$ . Set container 4 on top of container 7.

When backfilling is employed, containers 7 and 4 would be put back into the stack where they used to reside.

## 5 Model implementation

The described model is implemented in NetLogo, an agent-based simulation platform and programming language (Wilensky, 1999). In this study, we modelled four yard blocks, each one with 40 bays of 40-foot containers, and each stack has six rows of containers that can be stacked up to four high. The cranes can move around these four blocks and can position themselves at any bay. The model is implemented to work for any number of cranes. The containers are distributed randomly across the four blocks and never more than four high in any one row. We also implemented trucks, each of which is assigned a randomly chosen container. If there is another truck already waiting at the bay where the container resides then the truck is made to wait in a holding area until the other truck is serviced and departed, thus clearing the spot for the waiting truck.

Our model implements a discrete simulation where every tick corresponds to one second of real-world time. At every tick, the model creates and positions any new trucks that might have arrived during that tick, asks the cranes to perform their chosen action for that tick, and updates the graphs and plots. Since the cranes' actions take more than one second to execute, the model incorporates wait times for each action. For example, it

takes six seconds for the crane to move from one stack to the next one. Instead of having the crane move one sixth of the distance each time, the model makes it wait for the first five seconds and then perform the move on the sixth second. This delay technique is used for all other actions: moving a container from one stack to another (40 seconds) and moving a container from a stack to the truck (87 seconds). By using this wait technique, it is easy to change the times each action takes, and thereby making the model robust and adaptable. It also enhances the animation by displaying an accurate representation of what is happening in the model.

**Figure 7** Implementation methods

---

```

main()
1 while user has not stopped program
2 do generate truck arrivals
3 for  $c \in C$ 
4 do  $g_c \leftarrow \emptyset$ 
5  $c.go()$ 
6  $tick \leftarrow tick + 1$ 
go()
1 if  $g_c \in T$  or  $g_c = \emptyset$ 
2 then  $t^* \leftarrow \arg_{t \in T} \max u_c(t)$ 
3 if  $u_c(t^*) > u_c(g_c) + \text{decommitment-penalty}$ 
4   then  $g_c \leftarrow t^*$ 
5  $g_c^t \leftarrow \text{ticks-to-move}$ 
6 if  $g_c^t \neq 0$ 
7 then  $g_c^t \leftarrow g_c^t - 1$ 
8 return
9 if  $g_c \in T$ 
10 then move to the first in  $PATH(c, t)$ 
11 if we are at  $g_c$ 
12 then  $g_c \leftarrow \text{deliver-container}$ 
13  $g_c^t \leftarrow \text{ticks-to-deliver}$ 
14 else
15  $g_c^t \leftarrow \text{ticks-to-move}$ 
16 elseif  $g_c = \text{deliver-container}$ 
17 thenif container is the topmost container
18   then place container on truck
19      $g_c \leftarrow \emptyset$ 
20   else move topmost container to another stack (based on rehandling strategy)
21  $g_c^t \leftarrow \text{ticks-to-deliver}$ 

```

---

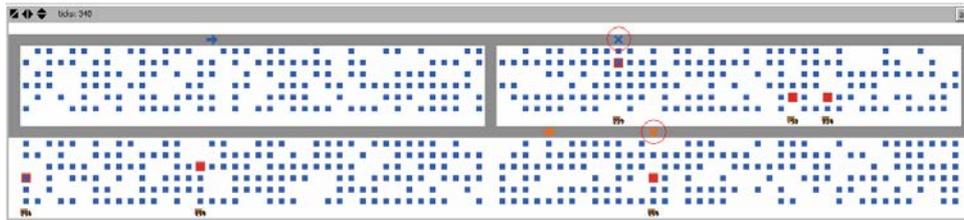
Notes: *main()* is the main loop and *go()* is a method implemented by every crane  $c$ .  
 Note that is assumed to be 0.

The model's logic is shown in Figure 7 in the form of pseudo code. At every tick, we first create any new trucks that might have arrived and assign them to their appropriate bay. The cranes are then asked to *go()*. First, each crane uses its utility function to determine the best truck for it to service. If the crane has a current goal of serving a truck, but there is a truck with a utility greater than the utility of the current goal plus the decommitment-penalty then the crane will switch its goal to the new truck, thus implementing (2), as shown in lines 1–5 of the *go()* procedure. Lines 6–8 implement the time delay (skipped ticks) required for some of the longer actions. In lines 9–15 the crane moves one step along its path towards its chosen goal and then either resets its goal or changes its goal to *deliver-container* (i.e., it is in position to deliver the container to the truck). Finally, in lines 16–21 the crane carries out the task of delivering the container to the truck. This task might require the crane to rehandle some containers if the target container lies underneath other containers. In these cases, the crane will rehandle as many containers as needed before making the *deliver-container* move.

## 6 Model validation

An innovative approach was taken to validate the developed model and its underlying utility functions. A modified version of the model was developed to allow actual yard crane operators to specify the locations of where the cranes should go next to provide service to the trucks. The two Xs in Figure 8 are the movable entities that can be used by the operator to indicate the position of where the each crane should travel to. In our study, the model generated a random sequence of truck arrivals and the operator was asked to move the Xs to indicate the locations of where the respective cranes would go next when confronted with the scenario of waiting trucks. Mr. Keith L. Nell from the Port of Charleston provided the operator input for our study.

**Figure 8** Modified version of model to elicit operator input (see online version for colours)

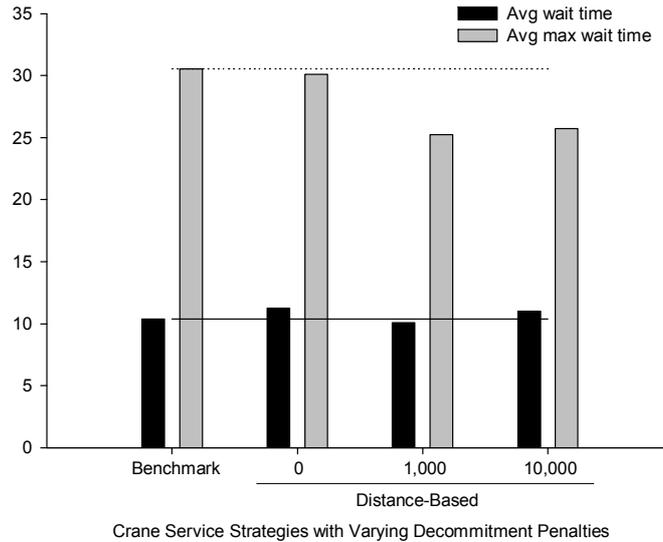


**Table 1** Performance measures from operator-input runs

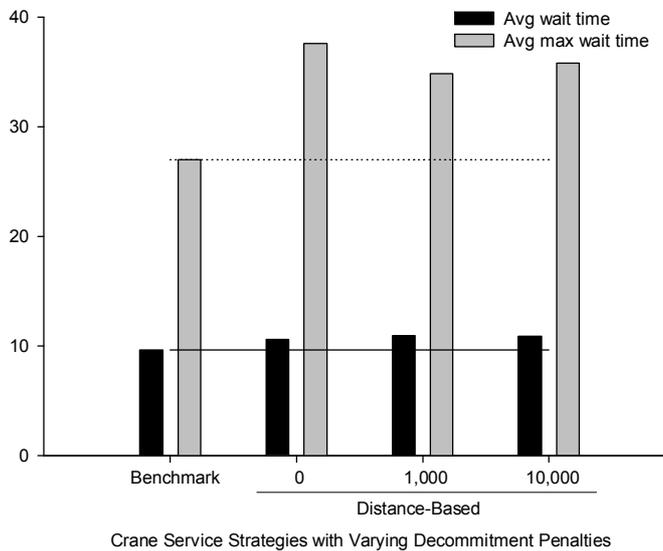
<i>Performance measure</i>	<i>Run #1</i>	<i>Run #2</i>
Max wait Time (min)	30.57	26.97
Avg. wait Time (min)	10.36	9.61
Crane 1 distance (mi)	1.33	1.62
Crane 2 distance (mi)	1.17	1.61
Crane 1 idle (%)	6.8	4.65
Crane 2 idle (%)	2.5	3.87

Two sets of runs were obtained from Mr. Nell. In each run, Mr. Nell was required to indicate the move-to position of the blue and orange yard cranes. Run number one had a total of 23 trucks serviced, and run number two had a total of 30 trucks serviced. Table 1 provides the key performance measures obtained from the two operator-input runs.

**Figure 9** Comparison of utility-based agents' decisions versus actual crane operator's decisions, (a) run 1 (b) run 2



(a)



(b)

Note: The distance-based utility function is tested with decommitment penalties of 0, 1,000, and 10,000.

Figure 9 shows the performance of the developed utility-based crane agents' decisions versus the actual crane operator's decisions in terms of truck wait time and maximum truck wait time. The performance measures shown for the utility-based agent strategies are averages from 100 simulation runs. As shown, the results obtained from the developed utility-based agent strategies are comparable to that of the operator's, with some producing even better performance. For example, in sample run number one, the distance-based strategy with a decommitment penalty of 1,000 yielded an average wait time of 10.05 minutes and average max wait time of 25.25 minutes, compared to the operator's 10.36 and 30.57, respectively. The *average max wait time* is defined as

$$\text{avg. max wait time} = \frac{1}{N} \sum_{i=1}^N \max_{t \in T} \text{WAIT} - \text{TIME}_i(t) \quad (4)$$

where  $i$  denotes the replication number and  $N$  is the number of replications (100).

It is clear from the comparative results shown in Figure 9 that the developed utility functions have captured the relevant decision variables and preferences of crane operators when deciding which truck to serve next.

## 7 Analysis of rehandling strategies

The experiments conducted in this study are intended to assess and compare the performance of the five mentioned rehandling strategies. Two particular metrics are used: average wait time per truck and average number of rehandles per yard crane. The lower the wait time, the less idling and the faster the truck is able to complete its transactions. The fewer rehandles the crane has to make, the more time it can spend servicing trucks. In essence, the lower these two metrics are the more efficient the terminal is.

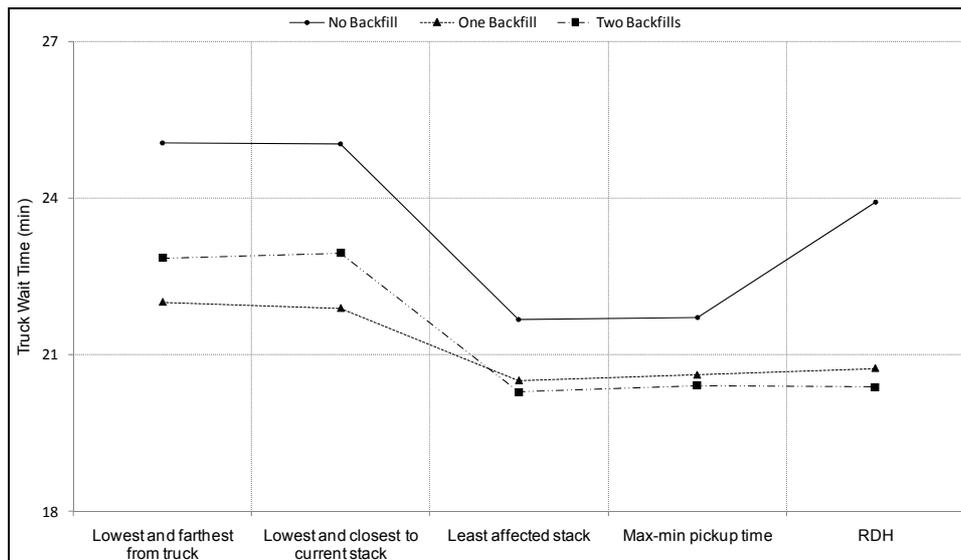
For the purpose of this comparison, the following model parameters are used:

- Trucks are assumed to arrive according to the Poisson distribution with a mean rate of ten trucks per hour per yard block. There are a total of four yard blocks.
- Yard cranes are specified to follow the distance-based utility. There are a total of two yard cranes available.
- Crane operators are opportunistic; hence, decommitment penalty is set to 0.
- Analysis period is set to three days (10 hours/day, total of 30 hours).
- Three values are tested for backfilling: none, one, and two. One backfill means that only one of the rehandled containers (specifically the top one) is backfilled into the empty stack, and two backfills mean that the top two containers that were rehandled are backfilled into the empty stack.
- The truck wait time and number of rehandles are averaged over 100 replications for each combination of rehandling strategy and backfill value.

The effect of the five rehandling strategies with different combination of backfills on truck wait time is shown in Figure 10. It can be seen that the two industry practices (lowest and farthest from truck and lowest and closest to current stack, will be referred to as the non-informed strategies) are the least effective. The poor performance by these

methods can be attributed to the lack of knowledge about truck arrivals. Without knowing which container maybe be picked up first, the crane operator will at times inadvertently place a container on top of one that will be delivered next. The two proposed strategies (max-min pickup time and least affected stack) outperforms the RDH. Collectively, it can be concluded that the strategies with truck arrival information perform better than non-informed strategies.

**Figure 10** Impact of rehandling strategy on truck wait time

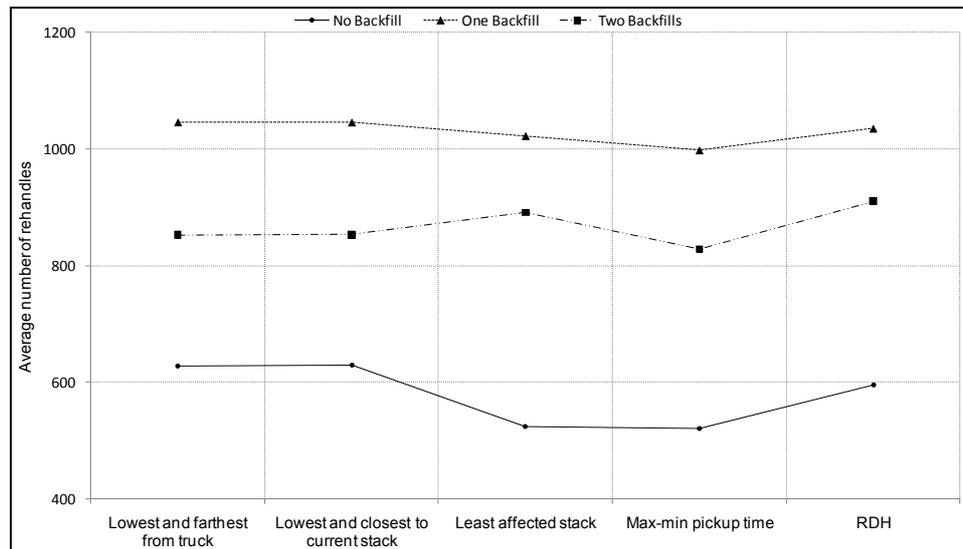


As shown in Figure 10, when backfill is employed it will lower the truck wait time significantly. Interestingly, for the non-informed strategies, one backfill is more effective than two backfills. This could be because without knowing which container will be delivered next, it is better for the crane operators to do just one backfill, essentially levelling the stacks, and then spend the remaining time servicing the next truck. For the informed strategies, two backfills is slightly better than one backfill. This result suggests that the more the crane operators do in levelling the stacks, the less likely the target container is buried underneath other containers and hence the lower the truck wait time. Note that even though two backfills are specified, if only one container is rehandled then just one container is backfilled.

In terms of the average number of rehandles for the two cranes, the three informed strategies outperform the non-informed ones when no backfilling is employed, as shown in Figure 11. The max-min pickup time strategy edges out the least affected stack strategy slightly, 520 versus 524 rehandles, and both of these strategies outperforms the RDH. As expected, when backfilling is employed, the cranes will have a higher number of rehandles. The significant difference in rehandles between doing one backfill versus two backfills is rather interesting. The results show that while two backfills will add more to the number of rehandles the cranes do after delivering the target container, in the long run their total number of rehandles is lower than if they were to backfill just one container. It can be concluded from these results that two backfills are more effective in lowering the average stack height; the lower the average stack height, the lower the

number of rehandles. In terms of the number of rehandles, when backfilling is employed, the informed rehandling strategies do not appear to have any advantage over the non-informed strategies.

**Figure 11** Impact of rehandling strategy on average number of rehandles



## 8 Concluding remarks and practical implications of findings

The developed agent-based model provides a powerful tool which terminal operators could use to assess the performance of various contemplated crane service strategies and rehandling strategies. A few rehandling strategies have been examined in this study, including the proposed least affected stack and max-min pickup time strategies, industry practices such as the lowest and farthest from truck and lowest and closest to current stack, and the RDH proposed by Zhao and Goodchild. Using the experimental parameters described in Section 7, the simulation results show that our proposed strategies work quite well compared to other strategies in reducing both the truck wait time and number of rehandles (with zero backfilling). Collectively, the results clearly demonstrate the benefit of having truck arrival information. With more motor carriers installing and utilising GPS tracking devices on their truck fleet, in the foreseeable future the terminal operators will have the necessary information about truck arrivals.

Our findings indicate that the proposed rehandling strategies, least affected stack and max-min pickup time, are equally effective. The least affected stack strategy produces a slightly lower truck wait time, and the max-min pickup time strategy produces a slightly lower number of rehandles. When using these strategies, additional reduction in truck wait time can be achieved with backfilling. Our analysis shows that two backfills is more effective than one; it provides a modest reduction in average truck wait time and a significant reduction in the average number of rehandles for each crane. A caveat with backfilling is that cranes will have to perform more moves which could lead to higher wear and tear on the cranes, fuel consumption, and labour resources. By following a

similar analysis as done in this study, terminal operators will be able to weigh the pros and cons of backfilling and quantify the expected benefits for their terminals.

### Acknowledgements

The authors would like to thank Mr. Keith L. Nell and Mr. Stevenson E. Kemp from the Port of Charleston for providing information regarding the service strategy of their yard cranes. Mr. Nell's assistance was instrumental in the calibration of the developed model. This paper also benefited from input from Mr. Rob Sawyer from the Port of Houston. Results and opinions expressed in this paper are solely of the authors.

### References

- California Environmental Protection Agency (EPA) (2009) *Drayage Truck Regulations*, available at <http://www.arb.ca.gov/msprog/onroad/porttruck/drayagetruckfactsheet.pdf> (accessed on 29 July 2009).
- Castilho, B. and Daganzo, C.F. (1993) 'Handling strategies for import containers at marine terminals', *Transportation Research Part B*, Vol. 27B, No. 2, pp.151–166.
- Gambardella, L.M., Rizzoli, A.E. and Zaffalon, M. (1998) 'Simulation and planning of an intermodal container terminal', *Simulation*, Vol. 71, No. 2, pp.107–116.
- Henesey, L., Davidsson, P. and Persson, J.A. (2009a). 'Agent based simulation architecture for evaluating operational policies in transshipping containers', *Autonomous Agents and Multi-Agent Systems*, Vol. 18, No. 2, pp.220–238.
- Henesey, L., Davidsson, P. and Persson, J.A. (2009b) 'Evaluation of automated guided vehicle systems for container terminals using multi agent based simulation', *Multi-Agent-Based Simulation IX: International Workshop*, Springer-Verlag, Berlin, Heidelberg, pp.85–96.
- Kim, K.H. (1997) 'Evaluation of the number of rehandles in container yards', *Computers & Industrial Engineering*, September, Vol. 32, No. 4, pp.701–711.
- Kim, K.H. and Hong, G.P. (2006) 'A heuristic rule for relocating blocks', *Computers and Operations Research*, Vol. 33, No. 4, pp.940–954.
- Kim, K.H., Park, Y.M. and Ryu, K-R. (2000) 'Deriving decision rules to locate export containers in container yards', *European Journal of Operational Research*, Vol. 124, No. 1, pp.89–101.
- Lee, D-H., Zhi, C. and Qiang, M. (2007) 'Scheduling of two-transtainer systems for loading outbound containers in port container terminals with simulated annealing algorithm', *International Journal of Production Economics, Special Section on Building Core-Competence through Operational Excellence*, May, Vol. 107, No. 1, pp.115–124.
- Lee, Y. and Lee, Y-J. (2010) 'A heuristic for retrieving containers from a yard', *Computers and Operations Research*, Vol. 37, No. 6, pp.1139–1147.
- Macharis, C. and Bontekoning, Y.M. (2004) 'Opportunities for OR in intermodal freight transport research: a review', *European Journal of Operational Research*, Vol. 153, No. 2, pp.400–416.
- McDowell, E., Martin, G., Cho, D. and West, T. (1985) *A Study of Maritime Container Handling*, Vol. 402, pp.1–10, Oregon State University, Sea Grant College Program, Ads, Corvallis, Oregon 97331.
- msnbc.com news service reports (2009) Updated 7:27 p.m. ET, Wednesday, 25 November 2009, available at [http://www.msnbc.msn.com/id/34147586/ns/us\\_news-environment/from/ET](http://www.msnbc.msn.com/id/34147586/ns/us_news-environment/from/ET) (accessed on 24 August 2010).
- Ng, W.C. (2005) 'Crane scheduling in container yards with inter-crane interference', *European Journal of Operational Research*, Vol. 164, No. 1, pp.64–78.

- Ng, W.C. and Mak, K.L. (2005) 'Yard crane scheduling in port container terminals', *Applied Mathematical Modeling*, Vol. 29, No. 3, pp.263–276.
- Park, T-K. and Kim, K.H (2010) 'Comparing handling and space costs for various types of stacking methods', *Computers and Industrial Engineering*, Vol. 58, No. 3, pp.501–508.
- Rebollo, M., Julian, V., Carrascosa, C. and Botti, V. (2001) 'A MAS approach for port container terminal management', *Proceedings of the Third Iberoamerican workshop on DAI-MAS*.
- Stahlbock, R. and Voß, S. (2008) 'Operations research at container terminals: a literature update', *OR Spectrum*, Vol. 30, No. 1, pp.1–52.
- Steenken, D., Voß, S. and Stahlbock, R. (2004) 'Container terminal operation and operations research – a classification and literature review', *OR Spectrum*, Vol. 26, No. 1, pp.3–49.
- Thurston, T. and Hu, H. (2002) 'Distributed agent architecture for port automation', *Computer Software and Applications Conference, Annual International*, pp.0–81.
- Watanabe, I (1991) 'Characteristics and analysis method of efficiencies of container terminal – an approach to the optimal loading/unloading method', *Container Age*, March, pp.36–47.
- Wilensky, U. (1999) *NetLogo*, Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL, available at <http://ccl.northwestern.edu/netlogo/>.
- Zhang, C., Wan, Y-W., Liu, J. and Linn, R.J. (2002) 'Dynamic crane deployment in container storage yards', *Transportation Research Part B: Methodological*, Vol. 36, No. 6, pp.537–555.
- Zhao, W. and Goodchild, A.V. (2010) 'The impact of truck arrival information on container terminal rehandling', *Transportation Research Part E: Logistics and Transportation Review*, Vol. 46, No. 3, pp.327–343.