A novel methodology for modelling yard cranes at seaport terminals to support planning and real-time decision making

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Abstract: This paper addresses the need by terminal operators to optimise the yard crane operations at seaport terminals. It introduces a novel agent-based approach to model yard cranes, where each crane acts as an autonomous agent that seeks to maximise its utility. A key component of the proposed agent-based simulation model is a set of utility functions that properly capture the essential decision making attributes of crane operators in choosing the next truck to serve. Simulation results reveal important insights about distance-based service strategy and time-based service strategy and how they can be used together to accomplish the terminal's operational objectives. The developed simulation tool can be used by terminal management to make strategic planning and/or real-time operational decisions to improve and optimise yard crane operations.

Keywords: seaport container terminals; simulation; yard cranes optimisation; truck service improvement.

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1 Introduction

The focus of this paper is on improving a critical element of port operations that has significant effects on port drayage truck operations – rubber-tired gantry cranes (known as yard cranes in the industry) service strategies. Port drayage is defined as a truck container pickup from or delivery to a terminal with both the trip origin and destination in the same urban area (Harrison et al., 2007). 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 (NOx), 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 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 entry 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 followed by the cranes in servicing the drayage trucks has significant effects on the average wait time of trucks and the maximum wait time of any truck.

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

1 the ratio of trucks to yard cranes

2 the yard crane service 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 is a more practical and less costly alternative for terminal operators, and hence, the focus of our research. While yard crane operators are given some general directions on how to serve the trucks, each operator is free to make his own decision. To date, very few studies have examined the effect of crane service strategy on truck turn time. This is in part because the yard cranes' work flow is not well understood and in part because of the inherent challenge in modelling the crane operator decision making process. Thus, it is unclear whether the current practice is optimal and how they could be improved. This study is motivated by the need for an evaluation tool to assess current yard crane operational strategies and to develop and evaluate alternative strategies under a variety of operational scenarios. It proposes a novel approach to modelling yard cranes by using agent-based modelling and utility maximisation techniques. The proposed methodology is robust and adaptable; it can be easily applied to study any marine container terminal.

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 proposed methodology, which includes discussions about the model and utility functions. Section 5 provides implementation details concerning the model. Section 6 explains the model validation procedure. Section 7 discusses the simulation results. Lastly, Section 8 provides concluding remarks.

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). Other good references include Crainic and Kim (2006) and Vacca et al. (2007). Generally, the literature on container terminals is classified into several categories: berth allocation, quay crane scheduling, ship stowage planning, storage activities in the yard, and allocation and dispatching of yard cranes and transporters. The yard crane scheduling problem addressed in this study falls under the last category. The following review is limited to published works that pertain to yard crane scheduling and agent-based simulation in the context of marine terminals.

The objectives of allocating and dispatching yard cranes and transporters are usually to minimise the total travel distance, the total waiting time, or the total delay to vessel or drayage trucks. The dispatching of transporters problem has been studied by researchers such as Bish (2003), Kim and Bae (1999, 2004), and Goodchild and Daganzo (2006). This study does not deal with transporters. Rather, it is focused on the yard crane scheduling problem. Previous related studies include the work of Ng (2005), Ng and Mak (2005), Zhang et al. (2002), Lee et al. (2007), Cheung et al. (2002), Lai and Lam (1994), and Lai and Leung (1996). 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 transporters. Given that the scheduling problem is NP-complete, these studies propose algorithms or heuristics in order to solve realistic size problems in a reasonable amount of time.

The research most related to this study is the work of Kim et al. (2003) which shares the same objective of determining the best sequence of trucks to serve by each yard crane, but their approach and assumption are different. Specifically, they proposed an approach where they used a dynamic programming model which assumed the arrivals of trucks are known in advance. In this work, our proposed simulation model does not require *a priori* knowledge of truck arrivals which is a more realistic representation of actual practice.

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 et al., 2009a), evaluation of operational policies in the transshipment of containers (Henesey et al., 2009b), quay crane scheduling (Thurston and Hu, 2002), container allocation to yard (Rebollo et al., 2001), and resource allocation (Gambardella et al., 1998).

To our knowledge, no agent-based simulation model has been developed to analyse yard crane service strategies and their impact on drayage operations. As stated previously, there is a need for such a model. The contribution of our work is two-fold. The first is that it provides a framework for modelling the yard crane operators' decision making processes, and the second is that it introduces a practical approach for simulating the yard cranes. The proposed methodology is robust and adaptable; it can be easily applied to study any marine container terminal.

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

2 stacked

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

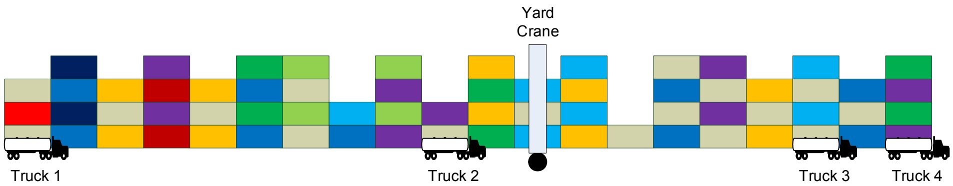
2 the terminal operator does not know in advance the order of trucks that will arrive to pick up import containers.

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 (industry term for reshuffle) 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.

The yard crane scheduling problem addressed in this study deals with the strategy the cranes employ in selecting the next truck to provide service to. Consider the scenario illustrated in Figure 2, there are several ways in which the crane could go about servicing the four trucks. One possible sequence is Truck 2, Truck 3, Truck 4, and Truck 1. Another possible sequence is Truck 2, Truck 1, Truck 3, and Truck 4. It is also possible for the crane to serve the trucks in this order: Truck 4, Truck 3, Truck 2, and Truck 1. It is evident that some sequences will be more effective than others in minimising the total wait time of the four trucks. Thus, the objective of the yard crane scheduling problem is to find the best sequence of trucks to serve to minimise the total truck wait time.

Figure 2 Illustration of yard crane scheduling problem (see online version for colours)



The yard cranes are operated by operators who are given some general guidelines, but who have the freedom to make judgment calls on how to move about the yard serving drayage trucks. The reason crane operators are given flexibility in deciding their work sequence is because at any given time, the yard cranes support multiple operations: vessel, drayage trucks, warehouse moves, rail moves, USDA moves, and Customs moves. There is not a centralised system that coordinates all of these movements and it is not known in advance when these activities will occur during the day. For these reasons, terminal operators will let crane operators decide what's best based on their knowledge of what is happening at the moment. Crane operators are directed by the foreman when they need to deviate from their usual plans. At the Port of Houston, the crane operators in general follow a distance-based strategy (R. Sawyer, personal communication). That is, they favour serving trucks such that their total travel distance is minimised. As illustrated in Figure 3, cranes at Port of Houston will first look to serve trucks waiting in the same yard block. As the crane travels in one direction (toward a truck) it will serve all trucks in the direction of travel. If there are no trucks waiting in the same yard block the crane is on, the crane operator first checks with the container yard management system to see if they are trucks currently at the gate coming to his block. If there are, he stays put. If not, he will look for trucks in other areas of the yard waiting for service. He will only travel to the truck in another yard block if he is the closest crane.

At the Port of Charleston, the yard cranes follow a similar service strategy as that at the Port of Houston (S. Kemp and K. Nell, personal communication). However, there are two distinct differences. The first difference is that at Charleston, the waiting time of a truck is factored into the crane operator's decision; crane operators can see when a truck is gated in via their computers that run the terminal's yard management system. That is, the crane operators at Charleston may skip nearby trucks to go serve a truck that has excessively long waiting time. The second difference is that at Charleston, the cranes follow a 'sweeping' strategy, meaning they prefer to move continuously from one end of the yard block to the other and serve most trucks along the way. Note that not all trucks in the sweeping direction of the cranes will be serviced. The exceptions are depicted in Figure 4. The two scenarios shown in Figure 4 illustrate how the sweeping strategy is abandoned by the crane operator in order to serve the longer waiting trucks first. When the operator does this, he is following a time-based strategy.

Figure 3 Port of Houston yard crane service strategy

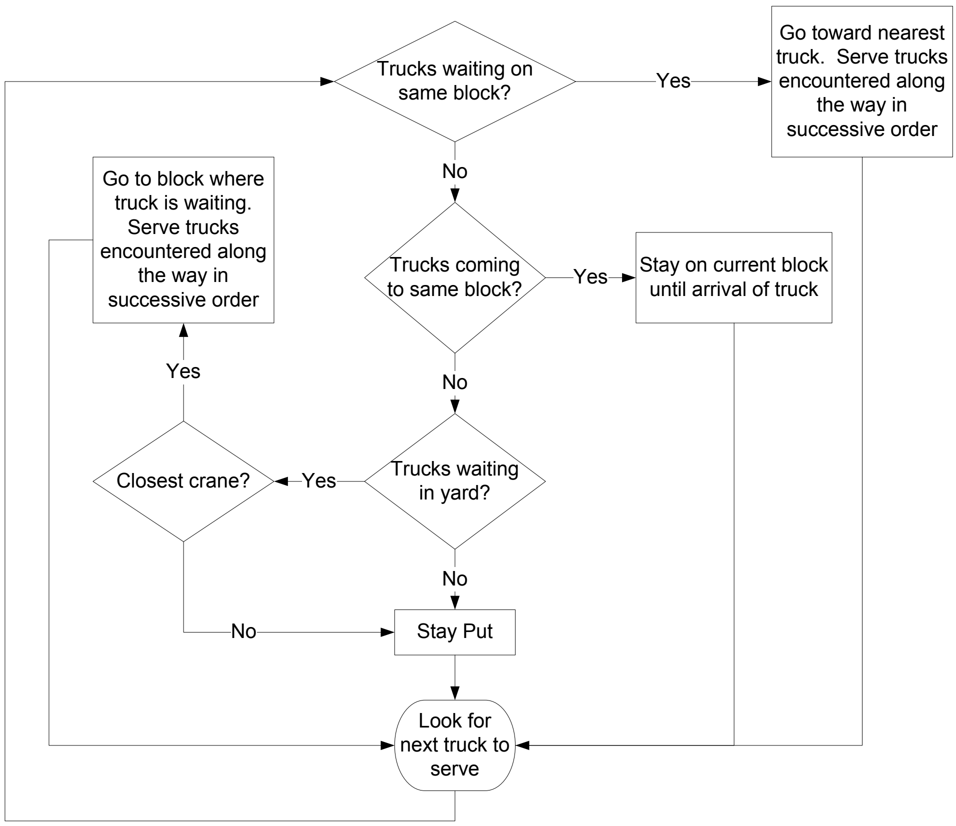
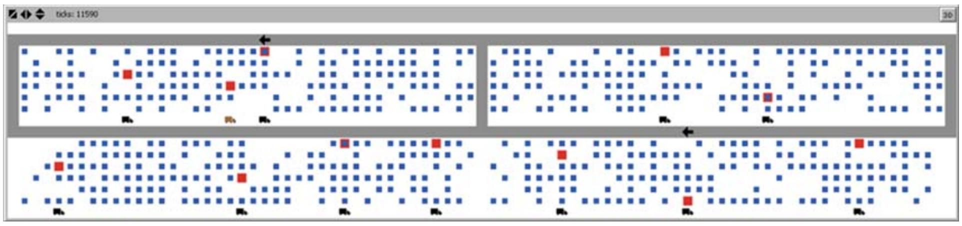


Figure 4 Port of Charleston yard crane service strategy: exceptions to sweeping strategy (see online version for colours)

4 Methodology

Given that, in actual practice, crane operators have the latitude to make their own decisions and do so in an autonomous and independent manner, the yard crane scheduling problem lends itself well to the agent-based approach. 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 5, 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. 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, $OTHER - CRANE?(p, c)$ and to be a Boolean function that returns 1 if p passes over some cranes other than c.

Figure 5 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 ($\varnothing$), 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. In actual practice, a crane operator may have decided to serve a truck on the opposite end of the yard block. As he begins to move the crane toward that truck, if another truck pulls up the yard block close to where he is, one operator may remain committed to serving the truck on the other end, but another operator may choose to serve the truck that just pulled up. Since each operator has a different philosophy about what is fair and efficient, it is necessary to capture this behaviour. 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 $g_c = (\varnothing)$ 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.

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

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

where $u_c(\varnothing) = 0$.

In this study, we developed two specific utility functions that capture the essence of how crane operators make their decisions as observed at the Port of Houston and Port of Charleston. The first one is a distance-based utility function which captures the effective distance between the crane and a truck, giving higher priority to trucks that are closer to the crane. This distance-based utility function, shown in (3), depends mostly on 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. Note that the path length is computed by using the shortest feasible travel path from the crane to the truck. The last term provides the cranes with as light implicit form of coordination. More formally, we define this utility as

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

where $p_1,\ldots,p_4$ are fixed penalty constants; p_1 and p_2 are set to 5,000 and p_2 and p_3 are set to 1,000. The p values are set to be greater than 1,000 because that is longer than any path. Note that the distance has a negative sign because the longer a crane has to travel the less utility it receives from that truck. *CHANGE – 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 *NOT – 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. Similarly, we define a time-based utility function that gives higher priority to the trucks that have been waiting the longer, but also taking into account the other terms. Formally, the time-based utility is given by

$$\begin{aligned} u_c^{time}(t) = \ &WAIT-TIME(t) - \\ &p_1 \cdot OTHER-CRANE?\big(PATH(c,t)\big) - \\ &p_2 \cdot HAS-TURN?\big(PATH(c,t)\big) - \\ &p_3 \cdot CHANGE-HEADING?\big(PATH(c,t)\big) - \\ &p_4 \cdot NOT-CLOSEST?(c,t) \end{aligned} \tag{4}$$

where *WAIT – TIME*(t) is the time that truck t has been waiting.

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 6 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.

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); note that we are only interested in modelling the time it takes a crane to rehandle a container and load containers, and thus did not explicitly model the micro-movements associated with these processes. 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 6 Implementation methods

main()
while user has not stopped program
do generate truck arrivals
for $c \in C$
do $g_c \leftarrow \varnothing$
c.go()
tick $\leftarrow$ tick +1

go()
if $g_c \in T$ or $g_c = \varnothing$
then t* $\leftarrow$ $\arg_{t \in T} \max u_c(t)$
if $u_c(t^*) > u_c g(g_c)$ + decommitment-penalty
  then $g_c \leftarrow t^*$
$g_c^t \leftarrow$ *ticks-to-move*
if $g_c^t \neq 0$
then $g_c^t \leftarrow g_c^t - 1$
return
if $g_c \in T$
then move to the first in $PATH(c, t)$
if we are at g_c
then $g_c \leftarrow$ *deliver-container*
$g_c^t \leftarrow$ *ticks-to-deliver*
else
$g_c^t \leftarrow$ *ticks-to-move*
elseif g_c = *deliver-container*
then take step in delivery
if container delivered
then $g_c \leftarrow \varnothing$

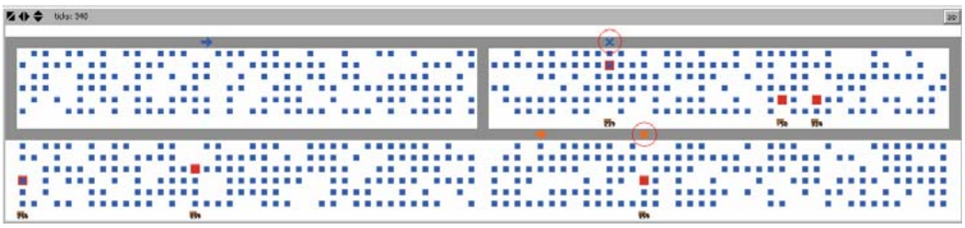
Notes: *main()* is the main loop and *go()* is a method implemented by every crane c.
Note that $u_x(\varnothing)$ is assumed to be 0.

The model's logic is shown in Figure 6 in the form of pseudo codes. 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 serve. 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 16–19 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 desired 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 blue and orange Xs in Figure 7 are the movable entities that can be used by the operator to indicate the position of where the cranes 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 such a scenario. Mr. Keith L. Nell from the Port of Charleston provided the operator input for our study.

Figure 7 Modified version of model to elicit operator input (see online version for colours)

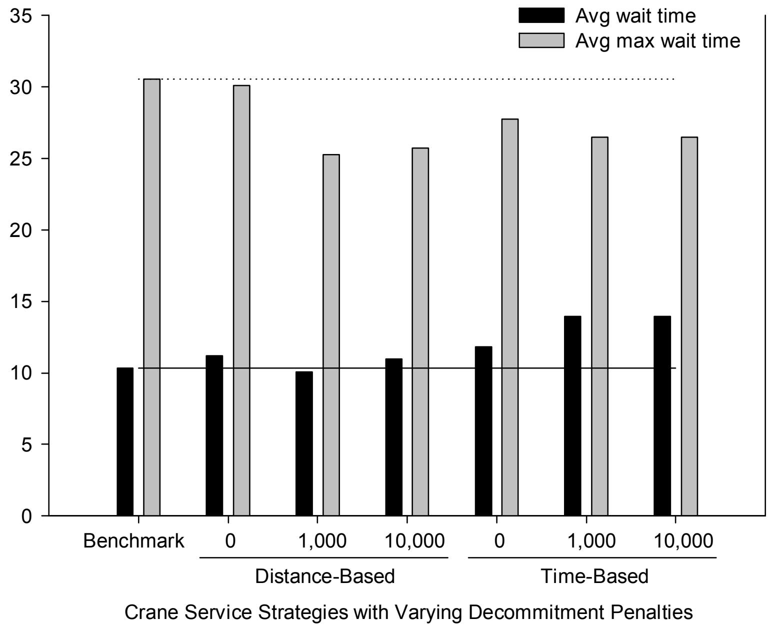


Two sets of runs were obtained from Mr. Nell. In each run, Mr. Nell was required to indicate the move-to position of the blue and orange yard cranes. Run number one had a total of 23 trucks serviced, and run number two had a total of 30 trucks serviced. Table 1 provides the key performance measures obtained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

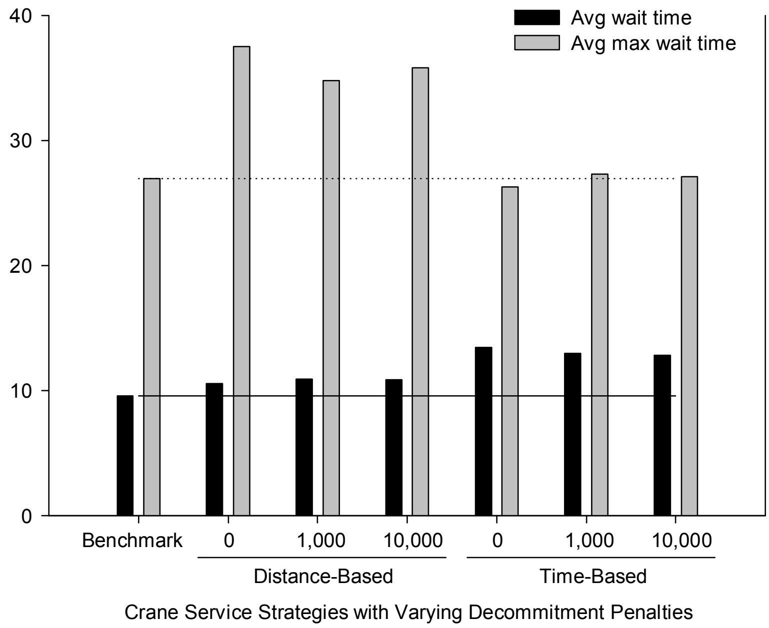
Table 1 Performance measures from operator-input runs

Performance measure	*Run #1*	*Run #2*
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

Figure 8 Comparison of utility-based agents' decisions versus actual crane operator's decisions, (a) run 1 (b) run 2



(a)



(b)

Note: The distance-based and time-based utility functions are tested with decommitment penalties of 0, 1000, and 10,000.

Figure 8 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. This was accomplished by playing back the exact same truck arriving patterns presented to Mr. Nell and having cranes use the developed utilities to pick the trucks to serve. 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

$$avg.\ max\ wait\ time = \frac{1}{N}\sum_{i=1}^{N} \max_{t\in T} WAIT-TIME_i(t) \tag{5}$$

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

It is clear from the comparative results shown in Figure 8 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 service strategies

The experiments conducted in this study are intended to uncover the intricate overriding decisions made by the actual crane operators (via the decommitment penalty parameter) and strategies that may lead to better performance overall (via the combinations of distance- and time-based utilities). Experiment 1 aims to answer the simple but important question to terminal operators of what is the reduction in truck wait time with each additional crane. The number of cranes tested ranges from 2 to 8. Experiment 2 aims to understand the benefit of having cranes switch from a distance-based strategy to a time-based strategy when the maximum wait time of any truck passes a specified threshold (will be referred to as distance/time-threshold strategy). This particular strategy is inspired by our observation of crane operator behaviour. Formally, this behaviour can be expressed as follows.

$$g_c = \begin{cases} t^* = \arg_{t\in T} \max u_c^{time}(t), & \text{if } \max\{WAIT-TIME(t)\} > threshold \\ t^* = \arg_{t\in T} \max u_c^{distance}(t), & \text{otherwise} \end{cases} \tag{6}$$

Three different threshold values are examined in experiment 2: 30, 45, and 60 minutes. Lastly, experiment 3 examines the benefit of utilising a medley of strategies where some cranes follow the distance-based strategy and some cranes follow the time-based strategy (will be referred to as the medley strategy). The motivation for this experiment stems from our discussions with the Port of Charleston crane operators. The idea behind this strategy is to determine if there is any benefit to having some cranes always looking to serve trucks on a first-come first-serve basis. In all three experiments, 100 replications are made with each replication simulating a ten-hour period. Trucks are assumed to arrive according to a Poisson distribution with a mean rate of ten trucks per hour to each yard block.

Table 2 The availability of cranes and their service strategy effects on truck wait times

Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*
			Two cranes distance-based			
0	14.37	41.30	16.02	16.12	6.87	6.70
1,000	15.42	37.93	16.33	16.29	7.08	6.83
10,000	15.04	45.65	16.16	16.51	6.64	5.75
			Two cranes time-based			
0	68.97	68.95	26.45	26.64	1.33	0.86
100	65.49	72.58	23.86	23.96	1.34	1.09
10,000	53.84	56.18	23.27	23.41	1.57	1.10

Table 2 The availability of cranes and their service strategy effects on truck wait times (continued)

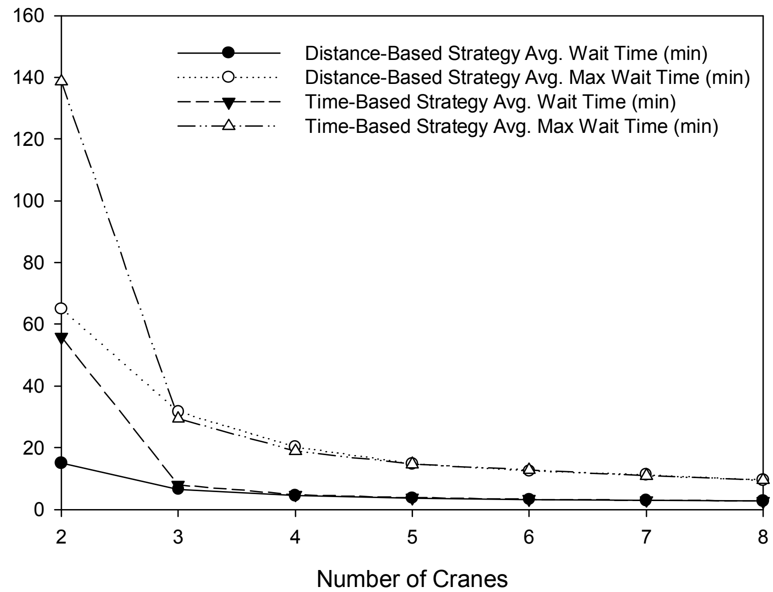
Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*
Three cranes distance-based								
0	6.48	31.54	13.18	13.55	13.14	30.90	29.55	30.86
1,000	6.69	29.22	13.56	13.75	13.52	30.14	28.91	30.07
10,000	6.64	28.30	13.90	13.65	13.76	28.64	29.95	29.92
Three cranes time-based								
0	8.65	31.80	15.54	15.66	15.58	24.85	25.17	25.10
100	7.91	28.99	14.72	15.06	14.92	27.62	26.27	26.65
10,000	7.94	29.37	15.00	14.99	15.31	26.29	26.40	24.97

Table 2 The availability of cranes and their service strategy effects on truck wait times (continued)

Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 4 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*	*Crane 4 Idle (%)*
Four cranes distance-based										
0	4.45	20.23	8.65	8.79	8.72	8.46	50.88	50.11	50.52	51.98
1,000	4.56	19.51	8.62	9.06	9.04	8.62	51.26	49.76	49.74	51.36
10,000	4.56	18.93	8.64	9.16	9.28	8.71	51.91	49.79	48.47	51.31
Four cranes time-based										
0	4.89	20.32	9.41	9.47	9.64	9.18	49.28	48.67	47.83	49.75
100	4.84	19.76	9.09	9.32	9.45	9.03	50.20	49.28	48.44	50.17
10,000	4.75	18.93	9.27	9.32	9.47	9.03	49.39	49.36	48.27	50.42

The detailed results of experiment 1 are shown in Table 2. In the interest of brevity and space limitation, Table 2 only shows the results for the two, three, and four crane cases, although experiment 1 tested up to eight cranes. It can be seen in Table 2 that the distance-based service strategy yields a lower average truck wait time for all three decommitment penalties, compared to the time-based strategy. An interesting finding from this experiment is how much better the distance-based strategy performs compared to the time-based strategy when the number of cranes available is small. The reason for this is evident when viewing the simulation. When the cranes follow the time-based strategy, they ended up making long runs from one end of the yard to another while ignoring nearby trucks. As shown in the right hand columns of Table 2, with two cranes, each crane on average covered a total distance of 16.24 miles when following the distance-based utilities and 24.60 miles when following the time-based utilities. When there are more cranes available, each crane has to cover less distance. Also, a crane's utilisation decreases significantly as the number of cranes increases. Hence, the performance gap between distance-based and time-based strategies decreases with additional cranes. With eight cranes, the average wait time and average maximum wait time are nearly equal. Figure 9 illustrates the reduction in truck wait times as the number of cranes increases.

Figure 9 Illustration of truck wait time reduction as number of cranes increases for distance-based and time-based service strategy



Another interesting finding from this experiment is how effective the distance-based utility is in minimising the maximum waiting time of any single truck. It was expected that the time-based utility with the decommitment penalty of 10,000 would yield the lowest average maximum wait time because the cranes would effectively 'chase' after the longer waiting trucks. However, as shown in Table 2 and Figure 9, the average maximum wait times of the time-based utilities are actually higher than that of distance-based utilities in most cases. Our simulation shows that when cranes 'chase' after the longer waiting trucks, they are less efficient because they are spending more time travelling to their target trucks. It would have been more efficient if they used that time to serve nearby trucks.

In regard to the number of suitable cranes needed to serve the four yard blocks, the simulation results suggest that there is marginal benefit beyond five cranes. A ratio of 1.25 yard cranes to 1 yard block appears to be adequate for the assumed truck volume and arrival pattern. Obviously, this ratio will need to be higher if there is a higher demand. Overall, the simulation results confirm the industry knowledge that a minimum of one yard crane is needed per yard block to provide satisfactory service and two yard cranes per yard block is more than adequate in most situations.

The detailed results of experiment 2, which aims to evaluate the performance of the distance/time-threshold service strategy, are shown in Table 3. Scenarios with 2, 3, and 4 yard cranes were examined. Results from this experiment indicate that trucks are better served if the maximum wait time threshold [see equation (6)] is higher. From the tested parameters, the combination of decommitment penalty being 0 and wait time threshold being 60 minutes yields the lowest average truck wait time for any given number of cranes, while the combination of decommitment penalty being 10,000 and wait time threshold being 60 minutes yields the lowest average maximum truck wait time for any given number of cranes. The reason the wait times are lower with a higher threshold is because the distance-based strategy is more effective than the time-based strategy at minimising the average maximum wait time, so it makes sense to delay the switch over for as long as possible. The benefit of having some cranes switch to a time-based strategy when a truck's wait time reaches the threshold (30 to 60 minutes) is that it ensures no truck will ever have to wait much more than the threshold. Because of the need to 'chase' the longer waiting trucks, the distance/time-threshold strategy underperforms the distance-based strategy when there are fewer cranes. However, with a ratio of at least one yard crane per yard block, this strategy outperforms the distance-based service strategy. Figure 10 shows the relative performance of this service strategy against others.

The detailed results of experiment 3, which aims to evaluate the effectiveness of the medley strategy, are shown in Table 4. Scenarios with 2, 3, and 4 yard cranes were examined. As expected the performance of the medley strategy is between the pure distance-based and time-based strategies. The crane idle percentages suggest that this strategy will lead to a more unbalanced work load among cranes because the crane(s) following the time-based strategy will have less idle time. While this strategy does not provide any improvement in truck wait time, it does yield a lower standard deviation in the maximum wait time compared to the distance-based and distance/time-threshold strategies (see Table 5). Thus, from a customer service standpoint, the medley strategy produces a more equitable service strategy since fewer trucks have to 'suffer' for the benefit of others. In Table 5, the medley strategy with two cranes involves one crane following the distance-based strategy and one crane following the time-based strategy, the medley strategy with three cranes involves two cranes following the distance-based strategy and one crane following the time-based strategy, and the medley strategy with four cranes involves three cranes following the distance-based strategy and one crane following the time-based strategy.

Table 3 Performance of distance/time-threshold service strategy for two, three, and four cranes

		Two cranes					
Decommitment penalty	*Wait time threshold (min)*	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*
0	30	72.42	199.94	25.75	25.66	1.84	1.44
0	45	53.85	152.01	23.68	23.73	2.88	2.40
0	60	34.61	108.45	20.35	20.31	5.03	4.43
1,000	30	56.48	153.18	23.33	23.52	1.72	1.36
1,000	45	45.52	127.97	22.13	22.22	2.90	2.45
1,000	60	23.94	75.44	18.51	18.56	5.07	5.20
10,000	30	53.63	138.23	23.07	23.13	1.90	1.26
10,000	45	41.60	115.06	21.63	21.82	2.92	2.19
10,000	60	22.27	72.60	18.31	18.43	5.31	4.60

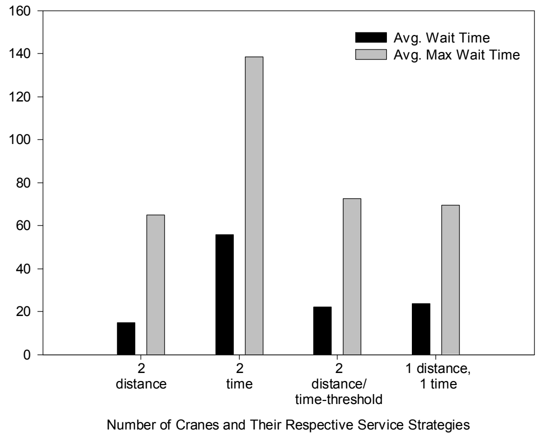
Table 3 Performance of distance/time-threshold service strategy for two, three, and four cranes (continued)

				Three cranes					
Decommitment penalty	*Wait time threshold (min)*	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*
0	30	7.10	30.66	13.96	14.08	14.20	28.91	28.49	27.84
0	45	6.52	30.86	13.16	13.39	13.34	31.12	29.94	30.39
0	60	6.48	30.34	13.12	13.36	13.39	31.07	29.59	29.85
1,000	30	7.09	30.01	13.86	13.97	14.11	29.34	28.73	28.58
1,000	45	6.71	29.82	13.59	13.69	13.42	30.07	29.38	30.68
1,000	60	6.73	30.55	13.70	13.62	13.47	29.89	30.05	30.22
10,000	30	7.07	29.06	14.01	14.08	14.26	29.04	28.80	27.71
10,000	45	6.77	30.83	13.64	13.90	13.82	29.78	28.68	29.21
10,000	60	6.77	28.95	13.64	13.81	13.86	29.77	28.86	29.25

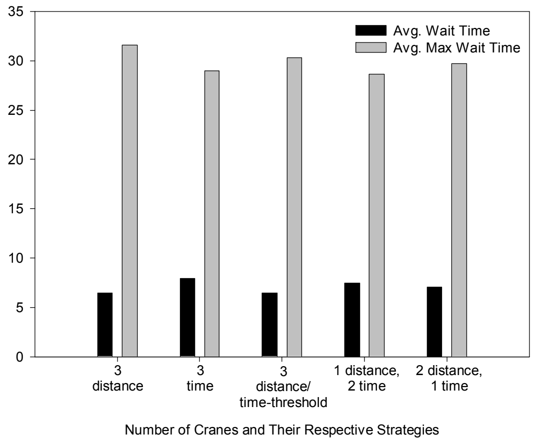
Table 3 Performance of distance/time-threshold service strategy for two, three, and four cranes (continued)

						Four cranes					
Decommitment penalty	*Wait time threshold (min)*	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 4 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*	*Crane 4 Idle (%)*
0	30	4.41	18.98	8.45	8.84	8.83	8.48	52.11	49.97	50.15	51.87
0	45	4.42	20.43	8.33	8.65	8.65	8.60	52.69	50.89	50.76	51.33
0	60	4.43	19.78	8.60	8.78	8.80	8.54	51.42	50.42	50.44	51.65
1,000	30	4.54	20.06	8.64	8.92	9.06	8.71	51.61	50.31	49.62	51.10
1,000	45	4.57	19.45	8.73	9.01	9.19	8.74	51.01	49.90	49.29	51.08
1,000	60	4.52	18.92	8.67	8.83	8.91	8.86	51.22	50.47	50.24	50.54
10,000	30	4.58	18.72	8.86	8.97	9.12	8.88	50.84	50.27	49.19	51.09
10,000	45	4.58	19.31	8.75	9.14	8.99	8.76	51.02	49.60	50.12	51.39
10,000	60	4.55	18.10	8.81	9.00	9.14	8.87	51.15	50.05	49.47	50.58

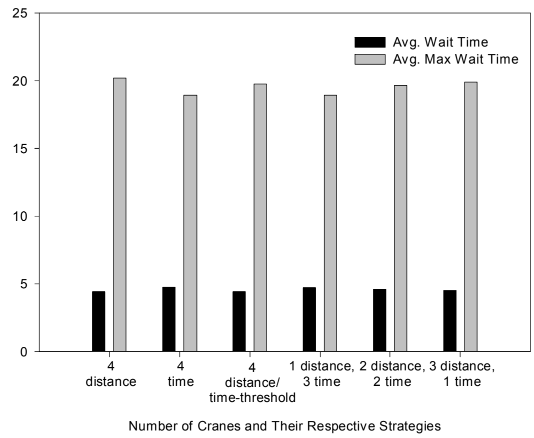
Figure 10 Comparison of different service strategies with (a) two cranes, (b) three cranes, and (c) four cranes



(a)



(b)



(c)

Table 4 Performance of medley strategy for two, three, and four cranes

Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*
Two cranes: one distance-based and one time-based						
0	26.81	83.74	14.82	21.86	4.56	1.70
1,000	24.41	70.92	14.90	20.96	4.53	1.97
10,000	23.55	69.56	14.92	20.88	4.61	1.95

Table 4 Performance of medley strategy for two, three, and four cranes (continued)

Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*
		Three cranes: one distance-based and two time-based						
0	7.83	31.67	13.46	15.33	15.31	28.93	26.10	25.77
1,000	7.56	30.13	13.87	14.84	15.10	28.30	27.26	26.03
10,000	7.48	28.63	13.96	15.02	15.07	28.56	26.10	26.45
		Three Cranes: two distance-based and one time-based						
0	7.08	31.55	13.21	13.43	14.91	30.07	29.46	27.85
1,000	7.15	30.50	13.74	13.92	15.05	29.15	28.09	26.36
10,000	7.02	29.72	13.73	13.70	14.81	29.20	29.85	27.37

Table 4 Performance of medley strategy for two, three, and four cranes (continued)

Decommitment penalty	*Wait time (min)*	*Max wait time (min)*	*Crane 1 Distance (mi)*	*Crane 2 Distance (mi)*	*Crane 3 Distance (mi)*	*Crane 4 Distance (mi)*	*Crane 1 Idle (%)*	*Crane 2 Idle (%)*	*Crane 3 Idle (%)*	*Crane 4 Idle (%)*
			Four cranes: one distance-based and three time-based							
0	4.78	19.95	8.56	9.31	9.46	9.22	51.37	49.94	49.01	49.79
1,000	4.75	19.13	8.71	9.34	9.15	9.06	51.10	49.30	49.96	50.38
10,000	4.71	18.96	8.92	9.24	9.22	9.33	50.27	49.92	49.73	49.16
			Four cranes: two distance-based and two time-based							
0	4.66	19.57	8.88	8.93	9.40	9.26	50.16	49.51	49.17	49.74
1,000	4.63	19.67	8.65	9.02	9.39	8.95	51.35	50.15	48.69	50.85
10,000	4.66	19.44	8.90	9.19	9.27	8.83	50.32	49.15	49.49	51.67
			Four cranes: three distance-based and one time-based							
0	4.51	19.90	8.45	8.94	8.83	9.12	52.11	49.51	50.36	50.21
1,000	4.64	19.73	8.84	9.04	8.97	9.22	50.27	49.71	49.64	49.76
10,000	4.61	19.40	8.80	9.15	9.14	8.95	50.61	49.39	49.27	50.94

Table 5 Comparison of maximum wait time standard deviations (minute) between the medley strategy and others

Number of cranes	*Decommitment penalty*	*Distance-based*	*Medley*	*Time-based*	*Distance/ time-threshold (60 min)*
2	0	10.91	24.55	70.20	62.66
	1,000	10.32	13.01	61.91	31.32
	10,000	9.82	15.76	53.67	30.00
3	0	6.95	5.29	4.97	5.34
	1,000	6.48	4.97	4.10	5.99
	10,000	5.00	4.91	4.21	5.20
4	0	4.47	3.96	3.82	4.46
	1,000	3.88	3.34	2.84	3.15
	10,000	3.37	3.58	3.68	3.59

Figure 10 provides a comparison of different service strategies for two, three, and four crane scenarios. The decommitment penalty is 0 for the distance-based strategy and 10,000 for the time-based strategy. For the distance/time-threshold strategy, the decommitment penalty is 0 and the threshold is 60 minutes. It can be seen in Figure 10(a) that with just two cranes servicing four yard blocks, the distance-based strategy outperforms all other strategies. With three cranes [Figure 10(b)], the distance/time-threshold strategy outperforms the distance-based strategy on the average maximum wait time, 30.34 versus 31.54 minutes, while their average wait time is equal at 6.48 minutes. With four cranes [Figure 10(c)], the distance/time-threshold strategy outperforms the pure distance-based strategy (4.43 versus 4.45 minutes for average wait time and 19.78 versus 20.23 minutes for average maximum wait time) because it achieves the same average waiting times while reducing maximum waiting times. It can be seen in Figure 10(c) that while the time-based and medley strategies do not yield a lower average wait time than the distance-based strategy, they all do provide a lower average maximum wait time.

8 Practical implications of findings and concluding remarks

Our findings validate the crane service strategies performed by operators at the Port of Houston and Port of Charleston. Specifically, it is found that while intuitive and straightforward the distance-based strategy is very effective. Surprisingly, it is even more effective than the time-based strategy in minimising the average maximum truck wait time. Our analysis of different service strategies supports the overriding decisions being made by crane operators at the Port of Charleston to abandon the ‘sweeping’ strategy (effectively the distance-based strategy) to serve longer waiting trucks. From the global optimisation perspective, our analysis shows that it would be best for the operators to abandon their ‘sweeping’ strategy when the wait time of the longest waiting truck exceeds a specific threshold; the higher this threshold the better the overall system performance. Such a strategy is termed distanced/time-threshold and it is found to outperform the distance-based strategy slightly. If a terminal operator is interested in providing more equitable service to truckers, it could utilise the medley strategy where some of the cranes follow the time-based strategy while the rest follow the distance-based strategy. As the ratio of yard cranes to yard blocks increases, the difference in performance between the different service strategies decreases. If the crane-to-block ratio is at least one and taking into account crane utilisation, the most straightforward and effective service strategy a terminal operator can employ is the distance-based strategy. If the container yard computer management system provides information about truck wait time (a typical commercial application does not provide this feature), then a slightly better strategy is to employ the distance/time-threshold strategy.

The developed agent-based model provides a powerful tool which terminal operators could use to assess the performance of various contemplated crane service strategies as well as the effect of having more cranes or fewer cranes due to mechanical problems and/or scheduled maintenance. A few practical service strategies have been examined in this study. The agent-based model and its underlying utility functions described here can easily be extended and adapted to test other possibilities as well as evaluate actual terminals. On this point, it is noted that our current implementation is fast enough for our needs, but it could be improved. Our analysis shows that line 2 of the go() procedure is where the simulation spends most of its time as each crane has to compute the utility for every single truck waiting in the container yard. We could easily overcome this limitation by using some fairly simple heuristics to eliminate some trucks from consideration. Implementing such heuristics was not necessary in this study since we are dealing with a fairly small problem. For more challenging problems, such heuristics will be needed.

The developed agent-based model can also be used to analyse the impact of various crane service strategies as well as the number of cranes on emissions. To quantify the reduction in emissions, the SmartWay DrayFLEET model, developed by the US EPA in collaboration with the Federal Highway Administration, could be utilised. By specifying the change in average truck turn time per transaction, the DrayFLEET model would compute the associated change in tons of pollutants (i.e., HC, CO, NOx, PM 10, PM 2.5, CO2). For example, if we use a generic port that has an annual throughput of 2,000,000 TEUs, a reduction of 10 minutes of turn time at the seaport terminal translates to a reduction of 14.9% in idle time and 0.9 to 1.5% in related pollutants. It is noted that while these emissions reductions are small at the regional level, the collective reduction at the national level may be much greater than the sum of its parts.

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