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An Agent-Based Approach to Modeling Yard Cranes at Seaport Container Terminals

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Abstract

Due to environmental concerns, terminal operators at seaport container terminals are increasingly looking to reduce the time a truck spends at the terminal to complete a transaction. For terminals that stack their containers, the solution may seem obvious: add more yard cranes to reduce trucks' wait time in the yard. However, the high cost of these cranes often prohibits terminal operators from freely buying more. Another reason is because there is no clear understanding of how the yard cranes' availability and service strategy affect truck turn time. This study introduces an agent-based approach to model yard cranes for the analysis of truck turn time with respect to service strategy. It is accomplished by modeling the cranes as utility-maximizing agents. This study has identified a set of utility functions that properly capture the essential decision making process of crane operators in choosing the next truck to provide service to. The agent-based model is implemented using NetLogo, a cross-platform multi-agent programmable modeling environment. Simulation results show that the distance-based service strategy produces the best results in terms of average waiting time and the maximum waiting time of any truck.

1. INTRODUCTION

Drayage activities play an important role in supply chain and logistics. From seaport terminals, drayage drivers and trucks transport import containers to first receivers where consolidation, stripping, transfers, and intermodal activities are undertaken. They also deliver containers to final receivers directly or via key rail intermodal terminals across the nation. This process is reversed for export containers. Drayage operations are now widely recognized as a critical emissions, congestion, and capacity issue for major container ports and rail intermodal terminals. Public agencies are rapidly developing policies and programs to reduce related emissions [e.g. 1]. Concurrently, drayage firms and terminal operators are working to improve drayage operations that are highly inefficient at the present. 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 [2]. In turn, high drayage costs seriously affect the profitability of an intermodal service.

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. Drayage trucks are diesel-fueled, heavy-duty trucks that transport containers, bulk, and break-bulk goods to and from ports and intermodal rail yards to other locations [3]. Truck idling in the queues is a contributing source of emissions and noise at 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. It is a measure of a terminal's efficiency in receiving and delivering containers. For terminals that stack their containers, demand is mainly the number of drayage trucks coming to the terminal to pick up or drop off containers. Supply is the number of yard cranes available to serve these drayage trucks. Supply is typically low on high volume vessel days because the majority of the yard cranes are assigned to work the vessel. In such a scenario, drayage drivers must wait for a longer period of time before a yard crane is available to perform the load or unload move. This waiting process can take a considerable amount of time.

The solution of adding more yard cranes to reduce truck turn time may seem obvious for terminals that stack their containers. However, the high initial investment, plus maintenance and operating costs of these cranes often prohibit terminals from freely buying more. Also, once a drayage truck arrives at its destination in the yard, its turn time is not only dependent on the number of cranes available, but also the service strategy in which the cranes follow. To date, no study has adequately examined the effect of crane service strategy on truck turn time. The challenging issues inherent in this problem, coupled with the limitation of existing research, motivate this study. In addition, this study addresses the practical challenges of increasing supply chain efficiency while reducing the carbon footprint. Specifically, this study investigates how to deploy yard cranes in an effective manner to reduce drayage trucks in-terminal wait time. 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 recognized by the Environmental Protection Agency (EPA) as a serious health issue.

The following describes the study's innovative, decentralized approach to model yard cranes by using agent-based modeling (ABM) and utility maximization to investigate the effectiveness of different crane service strategies. While ABM and Multi-Agent Systems (MAS) have been widely used in many different disciplines, they are relatively unexplored in the area of drayage and port operations.

2. LITERATURE REVIEW

Much of the research directly related to yard cranes' work schedule has been carried out using mathematical programming techniques (e.g integer programs or mixed integer programs). As such, these studies seek to optimize 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, and they could be either drayage trucks, or other yard handling equipment such as prime movers and internal transfer vehicles. Given that the scheduling problem is NP-complete, many studies proposed algorithms or heuristics in order to solve the real-world large-scale problem in a reasonable amount of time, including dynamic programming-based heuristic [4], branch and bound algorithm [5], Lagrangean relaxation [6], and simulated annealing [7].

In the study by Kim et al. [8], a simulation study was performed to compare the performances of several heuristic rules:

- First-come-first-serve: trucks are served in the order of their arrival time at the yard.
- Uni-directional travel: a yard crane travels in one direction and serves trucks until there are no more trucks remaining in the direction of the travel. After serving all the trucks in the direction of travel, the yard crane starts to travel in the opposite direction.
- Nearest truck first: a yard crane serves the truck that is located nearest to it.
- Shortest processing time: a yard crane serves the truck with the shortest transfer time, which is the sum of the travel time and the time for transferring the corresponding container to and from the truck. The transfer time includes the time for re-handling containers on top of the target container in the case of a delivery operation.

This study differs from the aforementioned mathematical programming related work in several ways. First, it takes a decentralized view instead of a centralized one. That is, the resulting cranes work flow is not governed by one optimal schedule. Rather the work flow stems from the individual decisions made by the crane operators. Second, it does not make any assumption regarding the ready times of the jobs. In this study, the number of drayage trucks that arrive to the yard is assumed to be Poisson distributed. Lastly, this study relies on agent-based simulation instead of a mathematical program. The agent-based feature also differentiates this study from the work of Kim et al. [8]. Moreover, each agent (i.e. crane operator) makes his decision based on a utility and not a prescribed heuristic rule.

3. PROBLEM DESCRIPTION

A typical drayage move involves either a delivery of an export container to the seaport terminal or pickup of an import container. A drayage driver arriving to pick up a loaded import container may encounter one of three basic systems.

- ***At wheeled terminals*** the driver will simply locate and retrieve the container on its chassis in the parking area.

- ***At stacked terminals***, the driver will usually first retrieve a chassis and then position the chassis in the container storage stacks to receive the container from a lift machine (typically yard crane).

- ***At some stacked and straddle carrier terminals***, the drayage driver will retrieve a chassis and then proceed to a designated transfer zone. A lift machine then brings the container to the waiting driver.

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 6 rows, and each row has 4 tiers (Figure 1). 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 facilitate the vessel operations. As import containers are discharged from a vessel, they are stacked in the allocated space without any segregation. Export containers, on the other hand, are methodically segregated by 1) vessel, 2) port of discharge, 3) size, and 4) weight. This is done so that when export containers are transferred from the yard to the vessel, no rehandling (i.e. reshuffling of containers to retrieve the desired one) is required. Note that both the import and export processes are done in a manner to minimize the turn-around time of vessels.

Figure 1. Illustration of bay, row, and tier in a yard block

Most U.S. seaport terminals use rubber-tired gantry (RTG) cranes, often referred to as yard cranes, to load and unload containers in the yard blocks. On any given day, the yard cranes are assigned to either support the vessel operation or support the road operation. Vessel operation has higher priority, so the number of yard cranes available to support road operation is the total number of yard cranes available minus the number of yard cranes assigned to vessel operation. Road operation refers to the landside process where drayage trucks come to drop off export containers and/or pick up import containers. Vessel operation refers to the waterside process where import containers are transferred from a vessel to the yard and export containers are moved from the yard to the vessel.

A typical import process involves a drayage driver moving a loaded container from the seaport terminal to the consignee location and then returning an empty to the terminal. The process of taking a loaded container out of the terminal begins with the shipping line in charge of the container requesting drayage service. The manifest is transferred to the drayage company and at the same time to the terminal. The drayage company then creates a pickup order and subsequently dispatches the driver. In order to take a loaded container out of the terminal the driver first arrives at the terminal gate. At this stage, the driver must scan or show his driver's license and then provide the container number to the gate clerk. He must also specify whether he needs to pick up a chassis. If there are no issues with his transaction, the driver receives a pick-up ticket and is cleared to enter the terminal. If the driver does not need a chassis, he then proceeds to the pre-designated pick up area and waits to be serviced by a yard crane.

Depending on the availability of yard cranes and their service strategies, this wait can be a source of extensive delay. Once the yard crane arrives at the bay where the truck has been waiting, the crane operator must locate the requested container and must often rehandle other containers on top before reaching the target container. After the container is loaded onto his truck, the driver must verify that it is the correct container and undamaged. He then must lock the chassis and proceed to the radiation inspection station. After the radiation inspection by Customs and Border Protection (CBP), the driver scans or shows the pick-up ticket and waits for the clerk to perform the damage inspection of the container and issues an Equipment Interchange Report (EIR), ending the out procedure and allowing the truck to exit the terminal.

The yard cranes are operated by operators who are given the freedom to make judgment calls on how to go about the yard to serve drayage trucks. At the Port of Charleston, the operators generally aim to minimize their travel distance and the trucks’ wait time. However, they are given the flexibility to pick the next truck that makes the best sense based upon all the information they may know. At the Port of Houston, crane operators are also given the flexibility to use their judgment. In a series of interviews with different operators there, they appear to follow a strategy that is more distance-oriented (Figure 2).

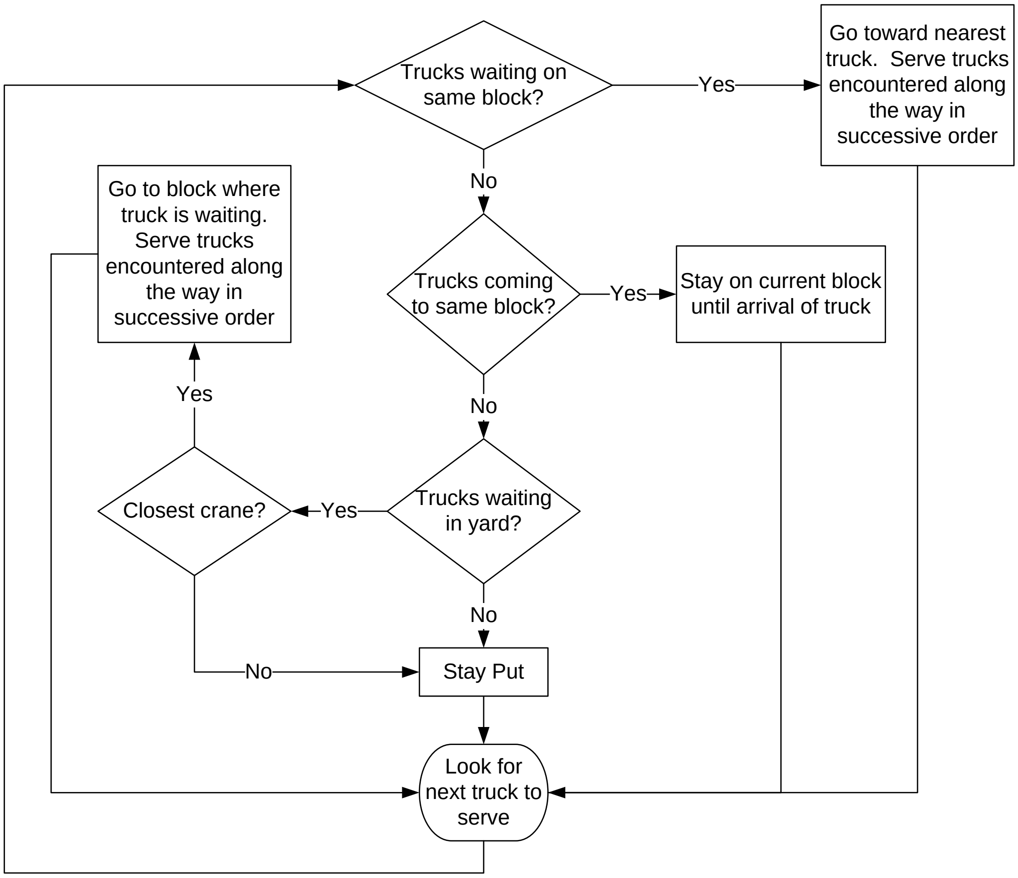

Figure 2. Port of Houston yard cranes service strategy

4. MODEL DESCRIPTION

To analyze the effectiveness of different yard crane service strategies, this study focuses on stacked terminals equipped with RTGs and on the import drayage process. Also, this study is focused entirely on the *container yard*. It does not consider the operations at the gate and berth. The model considers the case where a few yard cranes are responsible for serving the drayage trucks picking up import containers located in four different yard blocks. All containers are assumed to be 40 foot long, and each yard block is assumed to have 40 40-foot bays.

Figure 3 shows the general layout of the model. The cranes are represented by the arrows. For validation purposes, arrows are chosen because they provide a visual verification of the cranes' headings. The trucks are shown in brown and the import containers that need to be picked up are shown in red. Trucks are assumed to arrive according to the Poisson distribution with a mean rate of 10 trucks per hour per yard block. The gray areas denote the cranes travel paths. Note that there are actually four yard blocks.

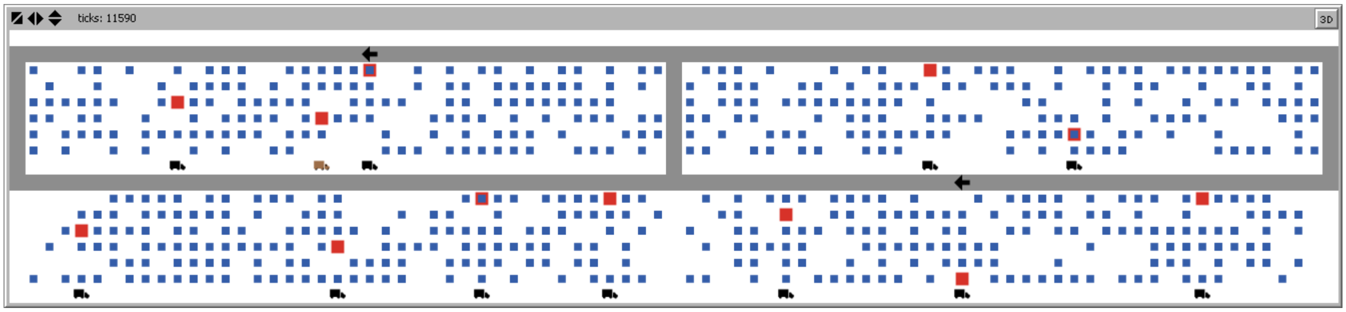

Figure 3. Agent-based model of yard cranes at a seaport container terminal

When available to work, each crane agent will evaluate the utilities of all trucks and will pick the truck i that has the greatest utility to serve. Three different truck utilities, based on actual real-world attributes (time and distance) and observations are developed for comparison purposes. Additional information about utility theory can be found in reference [9].

Distance-based utility function:

$$U(i) = 0 - \text{distance-to-crane} - \text{Penalty} \times \text{other-crane-in-path} - \text{Penalty} \times \text{turn-required?} - \text{Penalty} \times \text{change-heading?} - \text{Penalty} \times \text{not-closest-crane}$$

Time-based utility function:

$$U(i) = \text{truck-wait-time} - \text{Penalty} \times \text{other-crane-in-path} - \text{Penalty} \times \text{turn-required?} - \text{Penalty} \times \text{change-heading?} - \text{Penalty} \times \text{not-closest-crane}$$

Time-and-distance-based utility function:

$$U(i) = \text{truck-wait-time} - \text{distance-to-crane} - \text{Penalty} \times \text{other-crane-in-path} - \text{Penalty} \times \text{turn-required?} - \text{Penalty} \times \text{change-heading?} - \text{Penalty} \times \text{not-closest-crane}$$

The penalty in the above utility functions discourages a crane from choosing a truck that has another crane in its path, requires changing direction, requires changing heading, or has another crane closer to it. In addition to these fixed penalties, there is also a variable penalty (named de-commitment penalty) if a crane chooses to serve another truck with a higher utility while heading toward its intended truck (previously yield highest utility). Lastly, there is a lower bound for the utility; below which the crane will choose to stay put and not serve any truck.

In modeling the yard crane gantry speed and handling times, actual or 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 [10]. 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 twist lock
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

Our model is implemented in NetLogo [11], an agent-based simulation platform and programming language. We modeled 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 row to another (40 seconds) and moving a container from a row to the truck (87 seconds). By using this wait technique, it is easy to change the times each action takes to suit the real-world data.

Note that our implementation differs from the standard discrete event simulation only in that we allow certain monitoring actions to happen continuously. A standard discrete event simulator maintains a priority queue of (time, event) pairs, sorted by time. At each step the event with the smallest time is executed and any new events it generates are added to the priority queue. Adding a monitoring action such as "re-check utility function to make sure the current goal is still the best one," which has to be executed constantly because the value of the utility function can depend on time itself, can only be accomplished by adding an event that triggers at every step.

Our implementation has a main loop that is called at every tick (time step). At each tick we first create any new truck arrivals and then have each crane perform a move. Each crane maintains a goal variable which contains the name of the goal (goal.name) and the number of ticks that the crane must wait before performing an actual action (goal.ticks). The goal.ticks is equivalent to the time associated with an event in the standard discrete event simulations, except that the time in goal.ticks is relative to the current time. Only when goal.ticks is zero will the crane take an action towards its goal. In this way we simulate the fact that it takes many ticks for a crane to perform atomic actions such as moving from one bay to an adjacent bay. When a crane is ready to take an action and its goal is either empty or it has the goal to move to some specified bay, it first performs a check to ensure that its current goal is indeed the best one to have. If there is another goal with a utility that is greater than the current goal by at least de-commitment-penalty (0, 100, or 10,000) then it changes its goal to the new best goal. The crane then takes its actions, which will be either moving to an adjacent bay or moving the container and re-sets its goal.time. A pseudo code the program is provided below.

```
loop
  tick = tick + 1
  create arriving trucks based on poisson
  distribution
  assign new trucks to containers and have
  them wait if needed
  ask cranes to move
end

;the move function is performed by each crane
to move
  ;change the goal, if necessary
  if goal is empty or goal.name == "goto-
  position" [
    let goalp.position be the position of
    the truck that maximizes our utility-
    function
    if goal is empty or utility of goalp >
    utility of goal + de-commitment-penalty
    [
      goal.position = goalp.position
      goal.name = "goto-position"
      goal.time = ticks-to-move
    ]
  ]
  if goal is empty [
    return
  ]
  if goal.time != 0 [
    goal.time = goal.time - 1
    return
  ]
  if goal.name == "goto-position" [
    if we are located at goal.position [
      goal.name = "deliver-container"
      goal.time = ticks-to-deliver
    ]
    else [
      move one step towards goal.position
      set goal.time ticks-to-move
      return
    ]
  ]
  if goal.name == "deliver-container" [
    take step in delivering container
    if container has been delivered to
    truck [
      goal = empty
    ]
  ]
end
```

6. SIMULATION RESULTS

A common industry metric of the terminal performance as it relates to drayage is average truck turn time. In this study, the truck turn time is simply the wait time by the trucks for the cranes to travel to it and the time it takes the cranes to perform the rehandling and delivery moves. The trucks' average wait times are shown in column 2 of Table 1 (when there are two cranes available). These wait times are averaged over 100 simulation runs. It can be seen in Table 1 that the distance-based utility yields the lowest average truck wait time for all three de-commitment cases. When the de-commitment penalty is zero, it implies that the cranes should be opportunistic. That is, the cranes should evaluate the utilities of all trucks and serve the one with the highest utility at each time step. On the other extreme, a de-commitment penalty of 10,000 implies that the cranes should not be opportunistic. That is, the cranes should not serve other trucks (higher utilities at the present time) until they have completed service for their intended trucks (which previously yield the highest utilities). It makes sense that the average wait time for the distance-based utility is lowest when the de-commitment penalty is set to 0.

A surprising discovery from this study is how high the average wait time is when the crane operators follow the time-based utilities, compared to the distance-based utilities. As shown in Table 1, the resulting average wait times are almost four times higher than the distance-based utilities. Similarly, the time-and-distance based utility did not fare better. The reason for this is evident when viewing the simulation. When crane operators worked to minimize trucks' waiting time, they ended up making long runs from one end of the yard to another while ignoring nearby trucks. The model indicates that, on average, the two cranes covered a total distance of 16.25 miles when following the distance-based utilities and 25.41 miles when following the time-based utilities. The resulting effect is that many more trucks end up waiting longer.

Another surprising discovery from this study is how effective the distance-based utility is in minimizing the maximum waiting time of any single truck. It was expected that the time-based utility with the de-commitment penalty set to 10,000 would yield the lowest min-max wait time because the cranes would effectively "chase" after these longer waiting trucks. As shown in the third column of Table 1, the min-max wait times of the time-based utilities are higher than that of distance-based utilities. As explained above, when the cranes "chase" after the longer waiting trucks, they are less efficient because they are spending more time traveling to their target trucks. It would have been more efficient if they use that time to serve nearby trucks.

Table 2 shows the wait time and min-max wait time results when there are three cranes available. Note the significant drop in the average wait time and min-max wait time across all three utility types. It is also interesting to note that with three cranes, the performance of the time-based utilities and the time-and-distance-based utilities are very close to that of the distance-based utilities. This is because cranes do not have to cover as much distance with three cranes. The model indicates that, on average, the three cranes covered a total distance of 13.65 miles when following the distance-based utilities, 15.47 miles when following the time-based utilities, and 16.46 miles when following the time-and-distanced-based utilities.

Table 1. Simulation results for *2-crane* scenario

Distance-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	14.37	41.30
100	15.42	37.93
10,000	15.04	45.65

Time-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	68.97	68.95
100	65.49	72.58
10,000	53.84	56.18

Time-and-distance-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	68.04	86.38
100	65.42	67.97
10,000	52.24	56.77

Table 2. Simulation results for *3-crane* scenario

Distance-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	6.53	19.05
100	6.82	20.78
10,000	6.77	19.90

Time-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	8.75	21.95
100	8.51	24.47
10,000	7.85	21.27

Time-and-distance-based

De-commitment Penalty	*Average* Wait Time (minutes)	*Min of Max* Wait Time (minutes)
0	7.85	21.07
100	7.88	22.37
10,000	8.11	19.58

7. CONCLUSIONS AND LESSONS LEARNED

This study introduced an agent-based utility maximization approach to modeling yard cranes at seaport container terminals to study how different service strategies affect truck turn time. The developed model provides a powerful tool terminal operators could use to assess the performance of various contemplated crane service strategies as well as the effect of having additional cranes or fewer cranes due to mechanical problems and/or scheduled maintenance. This study has identified a set of utility functions that properly captured the essential decision making criteria of crane operators in choosing the next truck to provide service to. Simulation results showed that if crane operators choose trucks that are closest to them without requiring the cranes to turn often (a time consuming process) and reverse heading, then the overall system performance in terms of average waiting time and the maximum waiting time of any truck will be better than if there were to choose trucks based on their waiting times.

Implementing the mentioned agent-based simulation model revealed some important lessons in modeling cranes as agents. Initially, we implemented the crane behaviors as procedures (e.g. choose nearest truck or choose longest waiting truck). While these procedures were easy to implement in NetLogo, as we incorporated additional complexities into the operators' decision making process, the procedures became unwieldy. The procedures ended up implementing ad-hoc rules which we could not fully explain or justify. For these reasons, we changed our approach to use utility functions and made the cranes utility-maximizing agents. By using utility functions we can clearly and explicitly capture how the cranes balance the various priorities: distance to truck, time truck spent waiting, etc. A caveat here is that the utility functions can make it harder to implement certain procedural knowledge, like "move to the closest truck and then keep going in that direction if there are more trucks waiting right behind that one." In this study, we have identified a set suitable utility functions. In future work, we plan to combine procedural knowledge and communications between cranes with their individual utility maximizing behaviors.

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Biography

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