Vehicle Distance Threshold for Quayside Operations of Container Terminals

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Abstract

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In container terminal quayside operations, vehicles play a vital role in shuttling containers between the quay and the yard. The problem of determining the vehicle fleet size to employ consists of determining the exact order of moves and the vehicles to perform these moves, but due to the stochastic nature of daily operations, the planned order of moves is unlikely to be followed. The only decision that remains constant for vehicles in quayside operations is the number of vehicles to employ. Container terminal operators would benefit from analytical methods that provide feedback into how quayside operations will perform for different vehicle fleet sizes under stochastic conditions. This thesis discusses the development of an analytical method called vehicle distance threshold for providing feedback for quayside operations of container terminals. The vehicle distance threshold provides insight into how different vehicle fleet size affects container terminal performance. In addition simulation studies are conducted to show the applicability and the robustness of the vehicle distance threshold. The results show that the vehicle distance threshold is able to provide insight into how the quayside operations will perform under different vehicle fleet sizes while being robust to delays and changes that occur in daily operations.

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DEDICATION

to my dear wife, Renee

Chapter 1

INTRODUCTION

Container terminals play an important role in the global container shipping industry. The number of containers handled at container terminals is estimated to increase from 650 million 20-foot equivalent units (TEUm) in 2013 to 980 TEUm in 2020, with a compound annual growth rate of 6.1% (Schfer, 2016) [17]. The increasing growth puts an increased importance on quayside operations of container terminals to meet this demand.

In container terminal quayside operations, vehicles play a vital role in shuttling containers between the quay and the yard. The problem of determining the vehicle fleet size to employ consists of determining the exact order of moves and the vehicles to perform these moves, but due to the stochastic nature of daily operations, the planned order of moves is unlikely to be followed. The only decision that remains constant for vehicles in quayside operations is the number of vehicles to employ. Container terminal operators would benefit from analytical methods that provide feedback into how quayside operations will perform for different vehicle fleet sizes under stochastic conditions.

1.1 Research Motivation

The problem of determining the optimal vehicle fleet size for quayside operations has been modeled in many different ways through optimization, simulation, and analytical methods. The issue with these models are that they determine the number vehicles and sequence of moves, but do not provide feedback into how quayside operations will perform when delays or changes happen. There is a disconnect in the research on how the decision of vehicle fleet size affects quayside performance under stochastic situations.

1.2 Research objective

The primary objective of this research is to develop analytical methods that will provide container terminal operators with a set of tools that provides feedback on the performance of quayside operations for the decision of the number of vehicles to employ. The analytical methods should be flexible enough to be applicable to container terminals of different configuration while providing the ability to analyze alternate scenarios of different vehicle fleet sizes.

Chapter 2

LITERATURE REVIEW

There has been considerable research into determining the optimal vehicle fleet size for quayside operations. This research falls into two categories: optimization and decision support systems (DSS). Optimization is applied to this area by developing container terminal and scenario specific optimization models to determine the optimal vehicle fleet size and sequence of moves. DSS provides insight into how vehicle fleet size affect different aspects of container terminal operations to help with decision making. DSS are also specific to the scenario and container terminal for which they were developed. Although considerable research has been conducted in determining vehicle fleet size for quayside operations, none have looked at providing feedback into how decisions in vehicle fleet size affect container terminal quayside operations performance under stochastic situations.

2.1 Vehicle Fleet Size Optimization

The literature presents a series of optimization models for determining optimal vehicle fleet size and sequence of moves for quayside operations. Chen et al. (2013) study the integrated crane and vehicle scheduling problem as a constraint programming model with the goal of minimizing the completion time of the last job. Vis et al. (2001) modeled the vehicle fleet size problem as a network and developed a minimum flow algorithm to solve the problem. He et al. (2015) study the integrated QC, yard crane, and vehicle scheduling problem with a mixed integer programming model with the objective of reducing the amount of energy consumption used by the container terminal. Beaujon et al. (1991) developed an optimization model on the interaction between the vehicle fleet size and vehicle scheduling. A network approximation is used to develop a solution procedure for this model. Koo et al. (2005) studied the vehicle sizing and routing problem in a static environment. The problem was modeled in a two phase approach by developing an optimization model for the vehicle fleet size to provide a lower bound and then using a tabu search to determine the optimal routes. Coslovich et al. (2006) present a decomposition approach of minimizing fleet operation costs by breaking it down intro three sub problems: the routing costs, the resource assignment costs, and container re-positioning costs. Kang et al. (2008) study the problem by using a cyclic queue model to examine steady state operations, which then yields the optimum fleet size for long-term operations. Vis et al. (2005) examine the problem of minimizing vehicle fleet size under time window constraints to understand the advantages of using buffer areas. The literature in the area of optimization are able to determine exact solutions for the vehicle fleet size problem under certain assumptions for specific container terminals, but these optimal solutions are not followed in daily operations due to delays and changes. According to Koo et al., determining the optimal vehicle fleet size and sequence of operations is a problem that is more difficult to solve than the traveling salesman problem, which is NP-hard (Koo et al., 2005) [12]. This implies that the optimal solution is computationally infeasible in real world applications and thus is difficult to apply to daily operations.

2.2 Decision Support Systems

The literature in DSS for container terminals fall into two categories: simulation and analytical models.

Ursavas (2014) develops a DSS that utilizes a dual objective optimization to give container terminal operators insight into quayside operations. Her DSS allowed for conflicting objectives to be considered such as cost and processing time. Sun, Lee, Chew, and Tan (2012) study a domain specific simulation tool and how it can be used to make everyday operational decisions. Kasilingam et al. (1996) study vehicle fleet size by using a simulation cost model to determine the optimal number of vehicles to use in a manufacturing system while keeping cost to a minimum. Petering (2011) developed a detailed container simulation model that considers the different interactions between resources such as yard congestion and resource constraints. This was to study different aspects of container terminal quayside operations to give insight into different container terminal characteristics and design. Bielli et al. (2006) developed a object oriented simulation tool and library built in Java to help in container terminal decisions. The objects were designed using UML diagrams. Yun et al. (1999) developed a object oriented simulation tool using SIMPLE ++ to help facilitate decision making.

Murty (2014) studied a variety of interrelated decisions made during daily operations at a container terminal. Algorithms and analytical models were developed to determine the optimal vehicles to assign to each QC in 30 minute intervals that incorporates shift constraints. Rajotia et al. (2010) study the problem of determining the optimal AGV fleet size by estimating the time it takes to complete a set of jobs. Van Hee et al. (1988) developed a heuristic for determining performance of vehicles in container terminals using queuing theory. Anderson (1982) study public transportation networks to determine the optimal fleet size using closed loop networks. Analytical models were developed by estimating total travel time and desired service level.

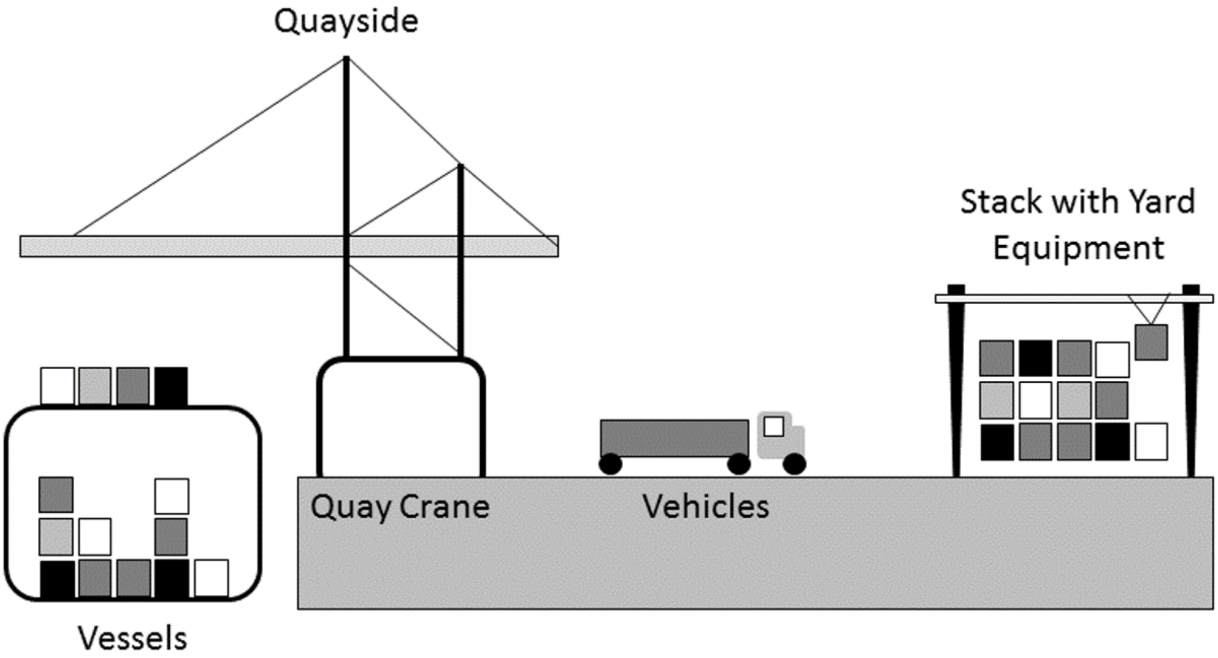
Though the above DSS are applicable to daily operations, the simulation models require experts to develop and maintain for daily use. The analytical models need estimations for input parameters or are only applicable to certain container terminals and scenarios. There is a gap in the literature for tools and methodologies that are applicable to most container terminals that provides feedback on how the decision of the vehicle fleet size affects quayside performance. Therefore, feedback into how the decision of determining the vehicle fleet size for quayside operations affects performance with applicability to all container terminals is a new and practical research topic that has not been addressed in the literature, and is the focus of this thesis.

Chapter 3

GENERAL PROBLEM DESCRIPTION

Container terminals are heterogeneous due to varying block size (from 10 to 50 containers in length), container terminal size, yard layout, vehicle type, and picking equipment. Quayside operations can be boiled down to a set of jobs of transporting containers from a pick up location to a delivery location (Briskorn et. al, 2007) [5]. These jobs can be classified into two distinct types, loading and unloading. A loading operation consists of a empty travel distance to the pick up location in the yard, a processing time at the yard, a travel distance to the drop off QC location, and a processing time at the QC (Figure 3.1). For any job, the

Figure 3.1: Quayside operations of a typical container terminal.



processing time at the yard or QC is the same, but the travel distance varies depending on the storage location in the yard.

Each QC has a designated set of jobs to process and a number of vehicles to transport these jobs. Depending on the distance of the job and the number of vehicles to process these jobs, there could be a delay at the QC. The problem consists of determining the number of vehicles to employ and the sequence of moves to maximize the productivity of QCs, while minimizing operational costs.

In Chapter 4 the simulation model used to study the vehicle distance threshold will be presented and in Chapter 5 a formulation for determining the vehicle distance threshold will be presented. The simulation study will provide insight into how productivity of QCs and vehicles are affected under different vehicle fleet sizes. In Chapter 6, the simulation model is validated with data obtained from a container terminal to demonstrate that it is able to represent the real world.

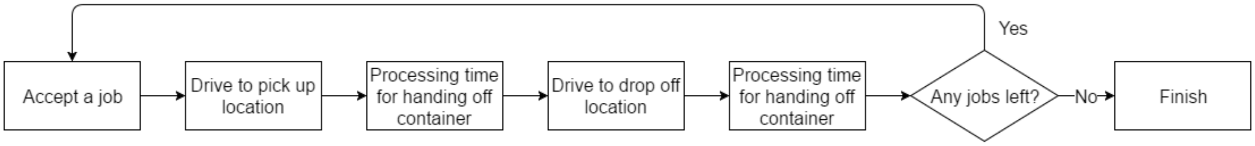
Chapter 4

SIMULATION MODEL

4.1 Model Design

The simulation model was designed to simulate quayside operations of QCs, vehicles, and yard picking equipment. The quayside operations is simplified to the flow of events outlined in Figure 4.1, which consists of a pick up location, a travel time, and a drop off location.

Figure 4.1: Flow of events in the simulation model.

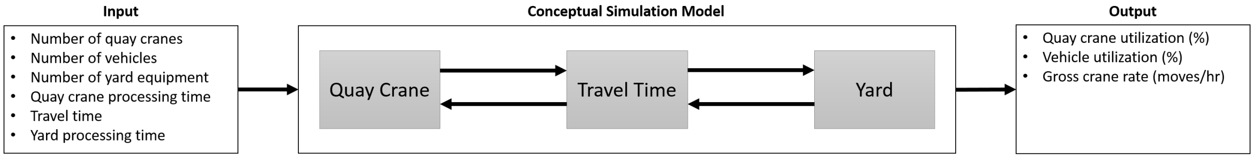


From the simplified flow of events, a conceptual simulation model was developed that is outlined in Figure 4.2. The model requires the following inputs: the number of QCs, the number of vehicles, the number of yard equipment, the QC processing time, the travel time, and the yard processing time. The simulation model consists of a number of QCs processing containers, a travel time for vehicles, and a number of yard equipment processing containers. The model outputs three metrics: QC utilization (%), vehicle utilization (%), and gross crane rate (moves/hr).

The model makes the following simplifications and assumptions. The model accommodates containers of only one size and type. This assumes that there is a similar processing time of containers regardless of size and type, and there is no interaction from outside vehicles as the study is focused on quayside operations.

Vehicles are assigned in a dedicated policy, this is where vehicles complete jobs only for

Figure 4.2: Conceptual simulation model of the quayside operations.



their assigned QC and vehicles can only handle a single container at a time. Vehicles travel a random amount of time to retrieve a container. There is also no congestion modeling in the yard as fleet size increases.

Each QC can only handle a single container at a time. QCs do not follow a fixed work schedule and will continuously work without delay; this is done to study the system at steady state.

At the beginning of each simulation run, the container yard starts empty and is filled to 50% of capacity. Each vehicle is assigned a job until all vehicles are busy. Once every vehicle is busy, steady state is reached and data collection begins.

4.2 General Setup for Experiments and Design

The simulation model was developed in Simio (Simio, 2016) [13]. In all simulation runs, data collection starts after every vehicle has a job and terminates after 24 hours of quayside operations. Each data point is the results of 20 simulation runs and all experiments record three metrics: QC utilization, gross crane rate and vehicle utilization. QC utilization is defined as:

$$QCUtilization = \frac{TotalTimeProcessing}{TotalSimulationTime} \tag{4.1}$$

Gross crane rate is defined as:

$$GrossCraneRate = \frac{NumberofContainersProcessed}{TotalSimulationTime * NumberofQCs} \tag{4.2}$$

Vehicle utilization is defined as:

$$VehicleUtilization = 1 - \frac{VehicleWaitTime + VehicleIdleTime}{TotalVehicleTime} \tag{4.3}$$

The value of the experiments constant parameters were chosen to be within realistic values based on information received from container terminal experts, professors, and from the literature review (Petering, 2011) [15]. The values were not based on a specific container terminal, but chosen to be realistic values to study container terminals in general. The default parameters are listed in Table 4.2. QC processing time is modeled as a triangular distributed random variable with mean 1.5 min, minimum 1 min, and maximum 2 min. This allows a maximum possible gross crane rate of 40 moves/hr. The yard picking equipment was based on yard cranes and the processing time in the yard is based on a gantry time plus a container processing time. The yard crane gantry time is modeled as a triangular distributed random variable with mean 1.0, minimum 0.7 min, and maximum 1.3 min min and the handling time is a triangular distributed random variable with mean 2.0 min, minimum 1.2 min, and maximum 3.4 min. The number of yard equipment was set to a value large enough as to not constrain the QCs. This was set this way as to study the effects of fleet size on QC performance and not introduce another factor into the experiments. These parameters remain unchanged across all experiments and studies.

Parameter	Value (minutes)
QC container handling time	Triangular(1, 1.5, 2)
Yard crane linear gantry time	Triangular(0.7, 1.0, 1.3)
Yard crane container handling time	Triangular(1.2, 2.0, 3.4)

Table 4.1: Default settings of simulation parameters.

4.2.1 Verification

Verification is the process of confirming the model is producing the expected results. Sun et al. (2012) states that the verification is the most important process in simulation development. To do this, an experiment was run using static parameters and then the results were compared to the expected values calculated through queuing theory.

Parameter	Value (minutes)
QC container handling time	1.5
Yard crane linear gantry time	1.0
Yard crane container handling time	2.0
Travel time	3.0

Table 4.2: Settings used to verify the simulation model results.

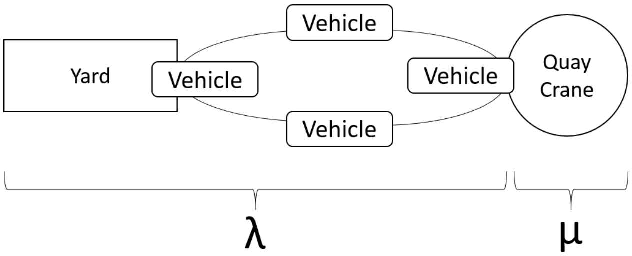
In queuing theory, there is an arrival rate and a service rate. By modeling the arrival rate as the time it takes for a vehicle to get back to the QC and the service rate as the QC processing time (Figure 4.3), we are able to apply queuing theory to calculate the QC utilization. Then by using the traffic intensity/utilization ratio (Equation 4.4) and adapting it to the quayside queuing model, we are able to calculate what the QC utilization should be (Equation 4.5).

$$UtilizationRatio = \frac{\lambda}{\mu} \tag{4.4}$$

$$QueuingQCUtilization = \frac{NumberofVehicles * QCHandlingTime}{YardHandlingTime + 2 * TravelTime} \tag{4.5}$$

The results of the experiment and calculations are presented in Table 4.3. The QC utilization from the simulation model results is similar to the values calculated using queuing theory. There is minor variation due to timing of when the data collection is started and

Figure 4.3: Quayside operations modeled as a queuing model.



ended due to a warm up period. From these results it can be seen that the simulation model produces the expected results.

Number of Vehicles	Simulation QC Util (%)	Queuing QC Util (%)
1	16.63%	16.67%
2	33.32%	33.33%
3	50.05%	50.00%
4	66.73%	66.67%
5	83.37%	83.33%
6	100.00%	100.00%
7	100.00%	100.00%

Table 4.3: Results from the simulation model and queuing theory calculations.

Chapter 5

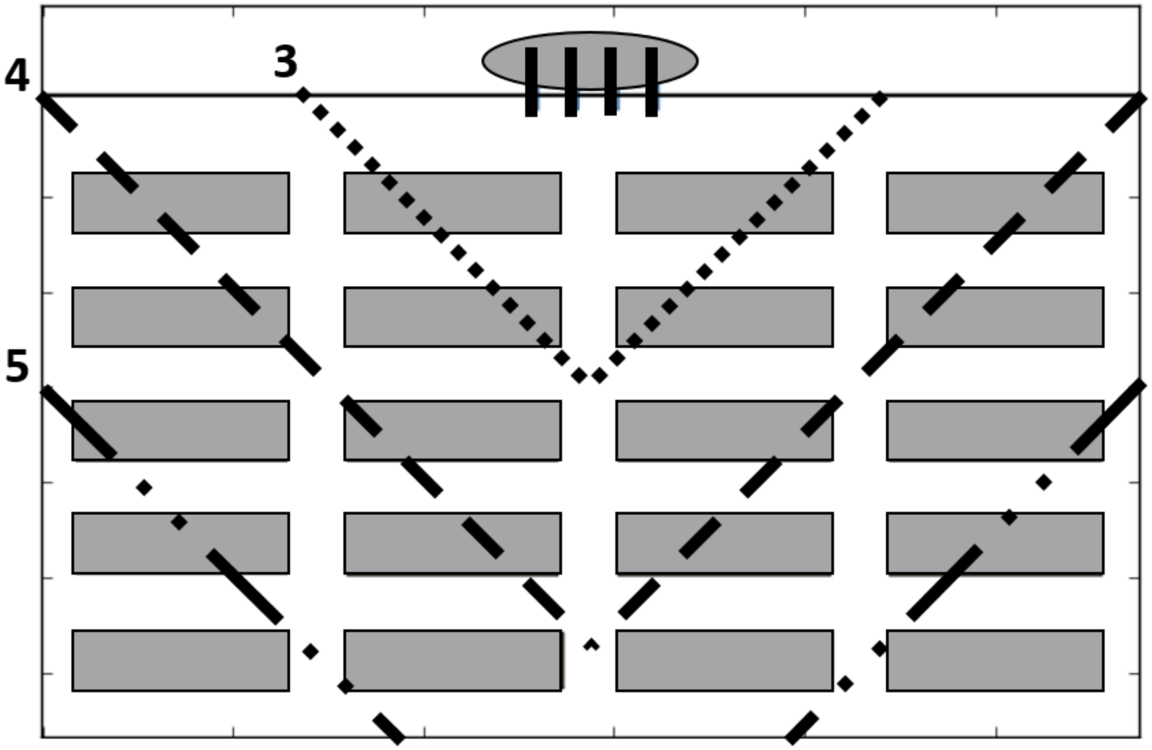
VEHICLE DISTANCE THRESHOLD AND SIMULATION STUDIES

5.1 Vehicle Distance Threshold

Rajotia et al. (2010) presented an analytical method to determine the vehicle fleet size to use in a manufacturing setting by analyzing the total time it takes to process a number of jobs and dividing it by the total time a vehicle is available. This solves for the number of vehicles by breaking each move down into the time takes to retrieve each container. But to accurately determine the time it takes to process a set of moves, a sequence must be determined or an estimation must be made. Building upon Rajotia's et al. (2010) work by analyzing the time it takes for a single move, the vehicle distance threshold was developed. The vehicle distance threshold is the distance at which if a job for a QC exceeds a certain travel distance it will cause a delay. The vehicle distance threshold depends on the number of vehicles for each QC, vehicle speed, QC processing time, and yard crane processing time. This is depicted in Figure 5.1, which shows the vehicle distance threshold plotted for different vehicle fleet sizes. We will start by defining the variables needed and then go into the formulation of the vehicle distance threshold.

Each QC is assigned a number of vehicles to shuttle containers to and from the yard; we can define this value as n. If the container terminal is using a dedicated policy, the number of vehicles are the ones assigned to it, but in a pooling policy the value is the ratio of the total vehicles divided by the number of active QCs. Each QC has a average processing time that we will denote as Q, each yard crane has a average processing time that we will denote as Y and each vehicle has an average speed v. For a given job j, the distance from vehicle i to the pick up point of job j is denoted by d^p_{ij}, and the distance from the pickup point of

Figure 5.1: Vehicle distance threshold plots for different vehicle fleet sizes (3, 4, and 5).



job j to the drop off point is denoted by d_{ij}^{d}. In a dedicated policy of vehicles the distance to the pickup and drop off point is the same, thus $d_{ij}^{p} = d_{ij}^{d}$ and will be defined as d_{ij}.

A QC with n vehicles assigned to it will never have a delay if a vehicle arrives before the QC has completed processing the current job. The time it takes for a vehicle to complete a job is defined as:

$$\frac{2d_{ij}}{v} + Y \tag{5.1}$$

Another way to look at this is that each vehicle has an allotted amount time to complete a job before it will cause a delay. The allotted time for a vehicle to complete a job without causing a delay is:

$$nQ \tag{5.2}$$

For there to be no delays for a QC then:

$$\frac{2d_{ij}}{v} + Y \leq nQ \tag{5.3}$$

Solving for the distance d_{ij}, the vehicle distance threshold for a job can be calculated by:

$$VehicleDistanceThreshold(d_{TH}) = max\left(0, \frac{(nQ - Y)v}{2}\right) \tag{5.4}$$

The vehicle distance threshold represents the distance a container can be from a QC before it will cause a delay. Table 5.1 shows the vehicle distance threshold for different vehicle fleet sizes with a vehicle speed of 25 km/hr.

Number of Vehicles	Time (seconds)
2	0
3	45
4	90
5	135
6	180
7	225
8	270
9	315

Table 5.1: The vehicle distance threshold of the one way travel time in seconds for different vehicle fleet sizes.

5.2 Simulation Study

In this section, the simulation model outlined in Chapter 4 will be used to study the vehicle distance threshold. The simulation study is intended to provide insight into container terminal performance with regard to the vehicle distance threshold and a sensitivity analysis will be done to see how the vehicle distance threshold perform as the input parameters are varied.

5.2.1 Study 1: Increasing Vehicle Fleet Size at a Large and Small Container Terminal

This study investigates how increasing the vehicle fleet size affects the QC and vehicle utilization for a fixed travel time around the vehicle distance threshold. The vehicle distance threshold hypothesizes that the QC utilization will increase as the vehicle to QC ratio approaches the vehicle fleet size indicated from the vehicle distance threshold, and then plateau for any vehicle fleet size larger. The study will also show that the vehicle distance threshold is applicable to quayside operations of container terminals regardless of size. Two experiments were designed to study increasing the vehicle fleet size at a small and large container terminal. For the small container terminal and the large container terminal, the input parameters are presented in Table 5.2 and 5.3. The number of QCs for a small container terminal was chosen to be 2 to represent a small vessel being serviced, and the number of QCs for a large container terminal was chosen to be 8 to represent multiple vessels being serviced. The travel time was calculated from the vehicle distance threshold to be 180 seconds, from the vehicle distance threshold this travel time matches a vehicle fleet size to QC ratio of 6. The QC and yard processing time were not changed. In both experiments, the vehicle fleet size to QC ratio is increased from 2 to 10 in increments of one.

Input Parameters	Values
Travel Time	180 seconds
Number of QCs	2
QC Processing Time	Triangular(1 , 1.5 , 2) minutes
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.2: The input parameters for the experiment of increasing vehicle fleet size at a small container terminal.

Input Parameters	Values
Travel Time	180 seconds
Number of QCs	8
QC Processing Time	Triangular(1 , 1.5 , 2) minutes
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.3: The input parameters for the experiment of increasing vehicle fleet size at a large container terminal.

The results for the small container terminal experiment is presented in Figure 5.2. The QC utilization is the lowest at 32% when the vehicle fleet size to QC ratio is the smallest at 2. As the vehicle fleet size to QC ratio approaches 6, which is the vehicle fleet size to QC ratio that is calculated by the vehicle distance threshold, the QC utilization increases linearly from 32% to 96%. For any vehicle fleet size to QC ratio greater than 6, the QC utilization plateaus at 100%. The vehicle utilization remains constant at 100% for any vehicle fleet size to QC ratio less than 6. As the vehicle fleet size to QC ratio is increased for values greater than 6, the vehicle utilization decreases. The decrease in vehicle utilization is less per vehicle as the vehicle fleet size to QC ratio increases above the vehicle distance threshold. For the large container terminal experiment, the results is presented in Figure 5.3. The results are nearly identical to the results obtained from the small container terminal. As the vehicle fleet size to QC ratio approaches the vehicle distance threshold, the QC utilization increases linearly and then plateaus at 100% for any vehicle fleet size to QC ratio greater than the vehicle distance threshold. The vehicle utilization remains constant for any vehicle fleet size to QC ratio smaller than 6, the vehicle fleet size to QC ratio calculate from the vehicle distance threshold. For any vehicle fleet size to QC ratio values greater than the vehicle distance threshold, the vehicle utilization decreases. But the decrease in vehicle utilization gets smaller as the vehicle fleet size to QC ratio increases away from the vehicle distance threshold.

Figure 5.2: The effects of vehicle fleet size on QC utilization and vehicle utilization for a fixed travel distance of a small container terminal.

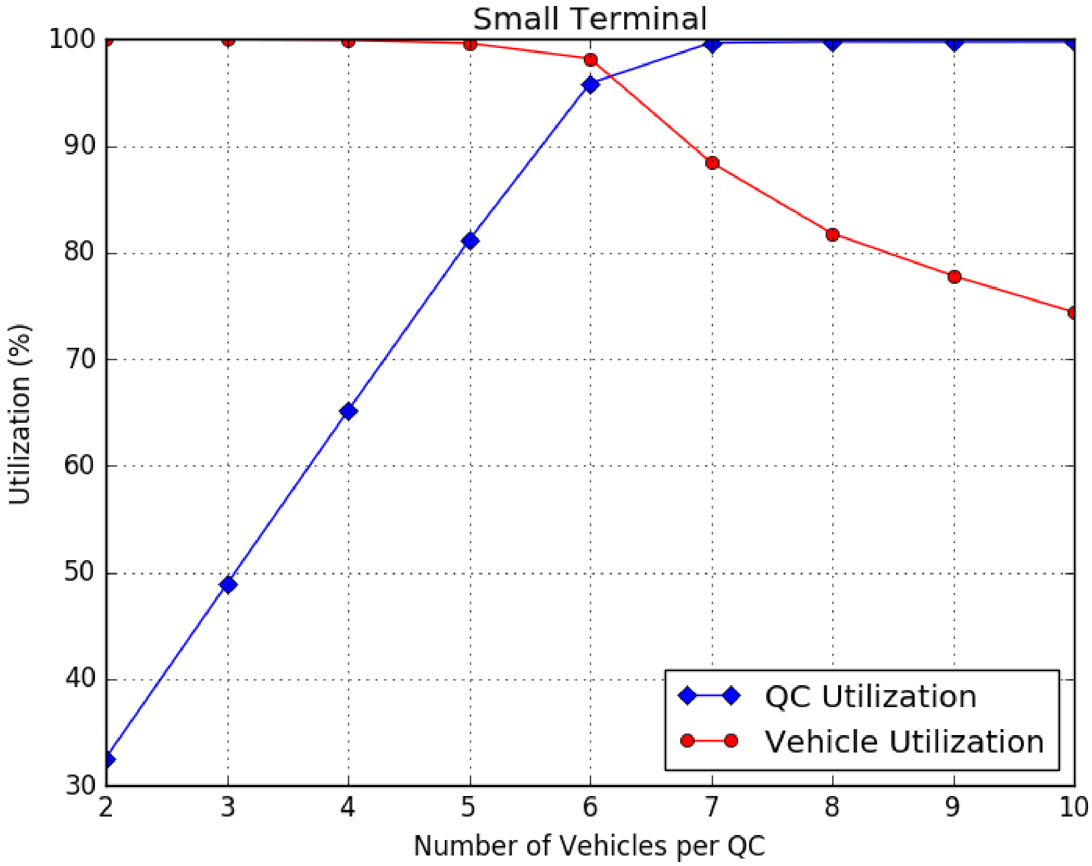
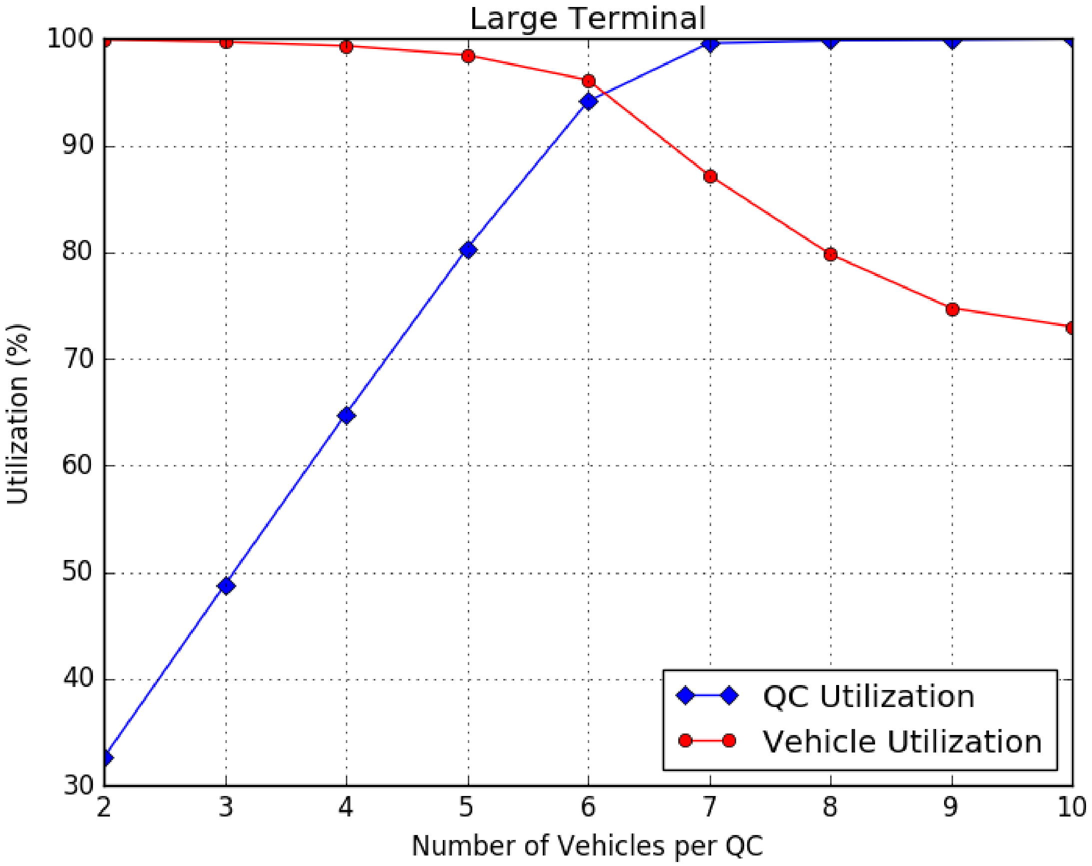


Figure 5.3: The effects of vehicle fleet size on QC utilization and vehicle utilization for a fixed travel distance of a large container terminal.



The results indicate that regardless of the size of the quayside operations, the container terminal performance is identical. This shows that the vehicle distance threshold scales to quayside operations of different sizes. The vehicle distance threshold is able to predict the vehicle fleet size at which the QC utilization is the max and the vehicle utilization will start to decrease.

5.2.2 Study 2: Travel Distance

Experiment 1: Increasing Static Travel Distance

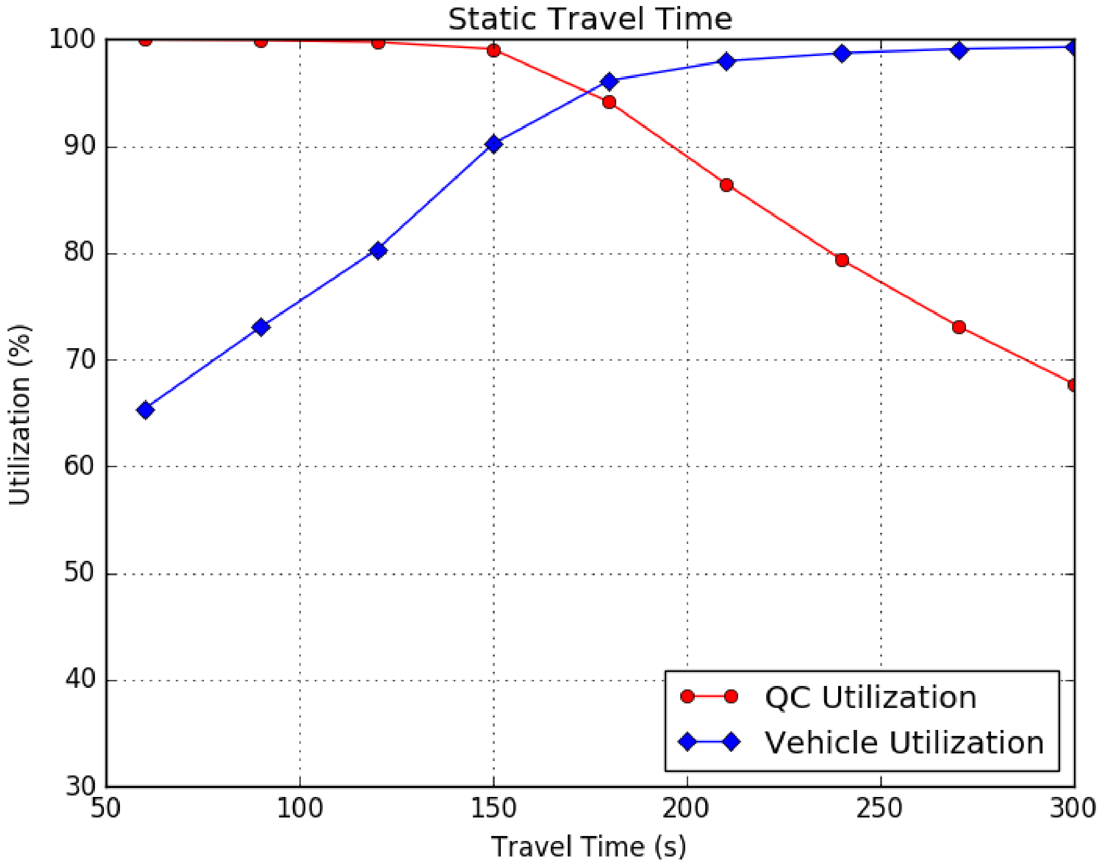
This study investigates how increasing static travel distance around the vehicle distance threshold affects the QC and vehicle utilization for a fixed vehicle fleet size to QC ratio. The vehicle distance threshold hypothesizes that the QC utilization will remain constant as the travel time approaches the travel time indicated from the vehicle distance threshold, and then decrease as travel time increases above the vehicle distance threshold. The input parameters for this experiment are summarized in Table 5.4. The vehicle fleet size to QC ratio of this experiment is 6 and from the vehicle distance threshold this equates to a travel time of 180 seconds. In this experiment, the travel time is increased from 60 seconds to 300 seconds in increments of 30 seconds.

Input Parameters	Values
Number of Vehicles	24
Number of QCs	4
QC Processing Time	Triangular(1 , 1.5 , 2) minutes
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.4: The input parameters for experiment 1 of varying static travel time.

The results for the increasing static travel time is presented in Figure 5.4. When the travel time is the smallest at 60 seconds, the QC utilization is the max at 100%. For any travel time smaller than the 180 seconds, the QC utilization remains constant at 100%. As the travel time increases greater than 180 seconds, the QC utilization decreases linearly from 95% to 68%. The vehicle utilization remains constant near 100%, when the travel time is greater than 180 seconds. For any travel time smaller than 180 seconds, the vehicle utilization decreases linearly from 96% to 65%.

Figure 5.4: The effect of travel distance on QC utilization for a fixed vehicle fleet size.



The results indicate that the vehicle distance threshold is able to predict the point at where the travel distance will start to have an affect on container terminal performance. The QC utilization starts to decrease when the travel time equals the vehicle distance threshold. Compared to the vehicle fleet size experiment, the travel distance does not have as much of an impact. Even when the travel distance is nearly double the vehicle distance threshold at 300 seconds, the QC utilization drops to 68%; while in the vehicle fleet size experiment, the QC utilization drops to 32%. QC utilization is less affected by travel distance, and thus container terminal operators should focus more on determining the vehicle fleet size.

Experiment 2: Varying Travel Distance Around the Vehicle Distance Threshold

This study was designed to provide insight into how the vehicle distance threshold is affected under realistic travel times. This study will also be used to represent how container terminal operator's might use the vehicle distance threshold to help decide the number of vehicles to employ.

The input parameters for this experiment are summarized in Table 5.5. The QC and yard processing times were not changed. The vehicle fleet size to QC ratio for this experiment is 6 and by using the vehicle distance threshold, this equates to a travel time of 180 seconds. The travel time in this experiment can is presented in Equation 5.5. The travel time is a Bernoulli random variable where the two possible outcomes are uniform distributions. So the travel time will reside below the vehicle distance threshold travel time with probability p and vice versa. The probability p is increased from 0% to 100% in increments of 10%. The travel time was designed this way to represent how a container terminal operator would make a decision by using the vehicle distance threshold. The container terminal operator will have to decide what is the best coverage of containers in yard given by the vehicle distance threshold. Should the operator employ a large vehicle fleet size to cover 100% of the containers in the yard or is there lower yard coverage that is acceptable. The travel time in Equations 5.5 is able to represent these different coverage percentages by adjusting the number of jobs that fall above or below the vehicle distance threshold.

$$(1-p) * Uniform(60,180) \quad \text{or} \quad p * Uniform(180,300) \tag{5.5}$$

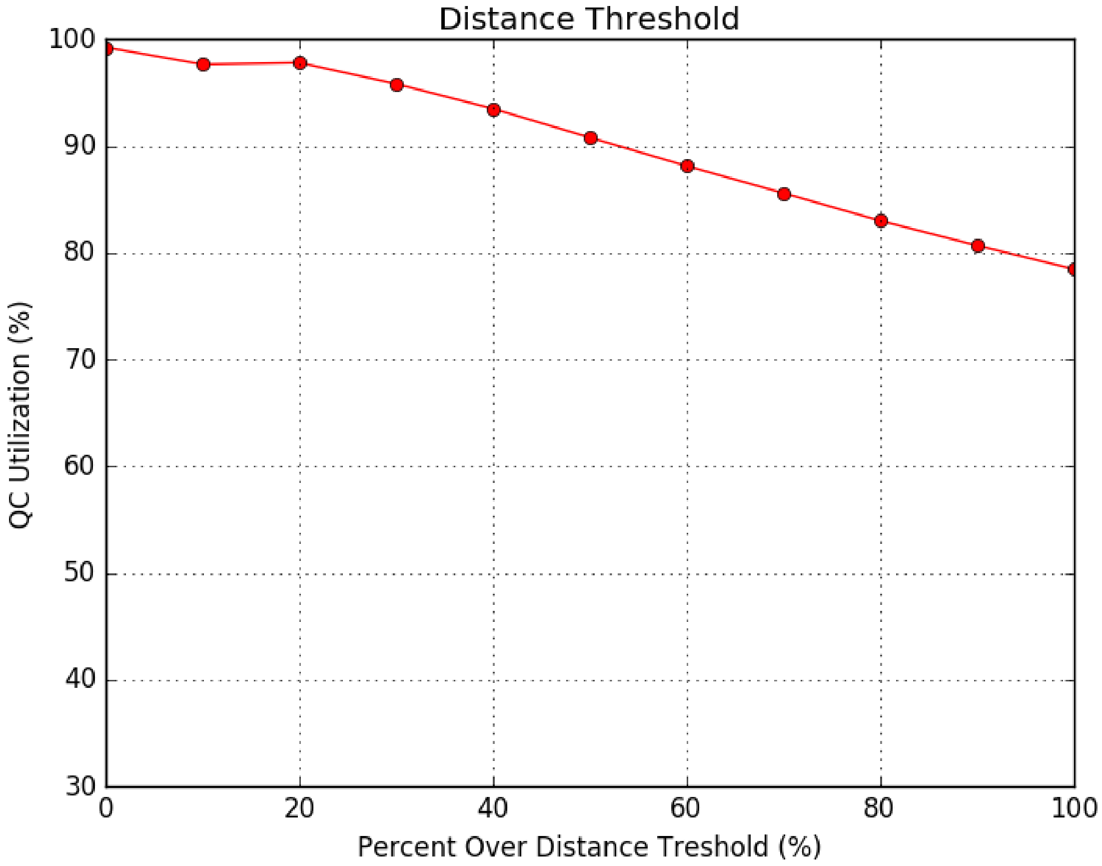
Input Parameters	Values
Number of Vehicles	24
Number of QCs	4
QC Processing Time	Triangular(1 , 1.5 , 2) minutes
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.5: The input parameters for experiment 2 of varying travel time around the vehicle distance threshold.

The results are presented in Figure 5.5. When the probability p is 0%, all of the travel time resides below the vehicle distance threshold and the QC utilization is the greatest at 100%. On the other hand, when p is 100%, the QC utilization drops to 79%. As p increases, the QC utilization decreases linearly.

The results help to support the vehicle distance threshold. The vehicle distance threshold states that when all of the travel time falls below the vehicle distance threshold, there should be no delays at the QC. From the results, this can be seen when p is 0%, the QC utilization is 100%. At the point at which the travel time falls above the vehicle distance threshold, QC utilization starts to drop.

Figure 5.5: The effect of percentage of distance over the vehicle distance threshold on QC utilization for a set vehicle fleet size.



5.2.3 *Study 3: Sensitivity Analysis*

This study investigates how changes in the parameters in the vehicle distance threshold affect the performance of a container terminal. This is meant to explore what parameters will have a greater influence on the vehicle distance threshold and also to explore how the vehicle distance threshold holds up to disruptions during daily operations. Four studies were conducted focusing on varying the processing time and increasing the range of the processing time distribution for both QC and the yard.

Quay Cranes Sensitivity Analysis of the Vehicle Distance Threshold

Experiment 1: Increasing QC Processing Time

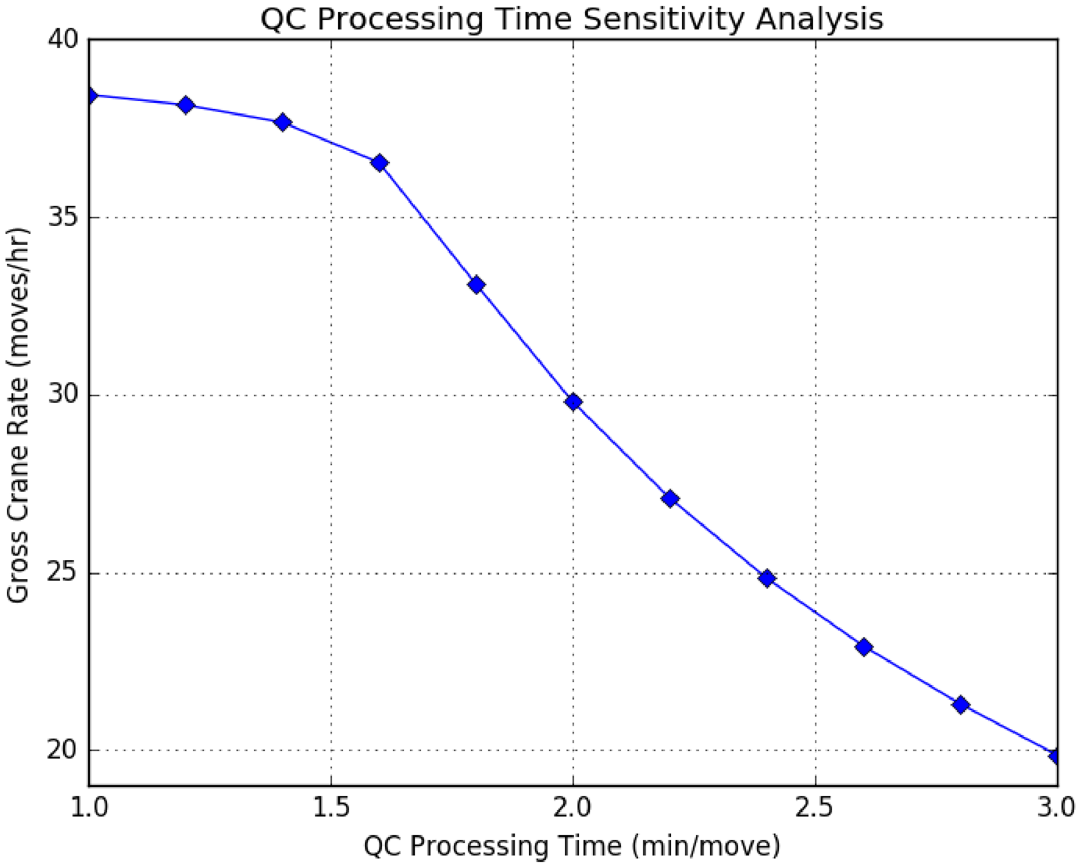
The purpose of this study is to investigate how the vehicle distance threshold responds to increases in QC processing time. The objective of this experiment is to see how large of an affect does the QC processing time have on the gross crane rate of a QC. The input parameters for this experiment are presented in Table 5.6. The vehicle fleet size to QC ratio for this experiment is 6. The travel time of 180 seconds was calculated from the vehicle distance threshold for a vehicle fleet size to QC ratio of 6 and the yard processing time was not changed. The QC processing time is increased from 1.0 minutes/move to 3.0 minutes/move in increments of 0.2 minutes/move.

Input Parameters	Values
Number of Vehicles	12
Number of QCs	2
Travel Time	180 seconds
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.6: The input parameters for experiment 1 of varying QC processing time distributions.

The results are presented in Figure 5.6. When the QC processing time is the fastest at 1.0 minutes/move, the gross crane rate is the highest at 38 moves/hour. As the QC processing time starts to increase, the gross crane rate remains relatively constant for QC processing times smaller than 1.5 minutes/move. As the QC processing time continues to increase, the gross crane rate decreases to a low of 20 moves/hour.

Figure 5.6: The effect of varying QC processing time distribution on gross crane rate.



When applying the vehicle distance threshold to this experiment, the QC processing time is 1.5 minutes/move. In Figure 5.6, this is the point where the gross crane rate starts to decrease linearly. This indicates that for faster QC processing times than the vehicle distance threshold, the gross crane rate will not increase by much. But when the QC processing time is slower than the vehicle distance threshold, the gross crane rate will be affected and start to decrease linearly. The QC processing time has a big impact on the gross crane rate, container terminal operators should place a emphasis on accurately determining this input value.

Experiment 2: Increasing the Range of the QC Processing Time

The second experiment is set out to investigate how the vehicle distance threshold responds to increases in the variability of the QC processing time. The objective of this experiment is to see how the vehicle distance threshold holds up to variability in the QC processing time. This is important to investigate as the QC processing time is bound to fluctuate during daily operations.

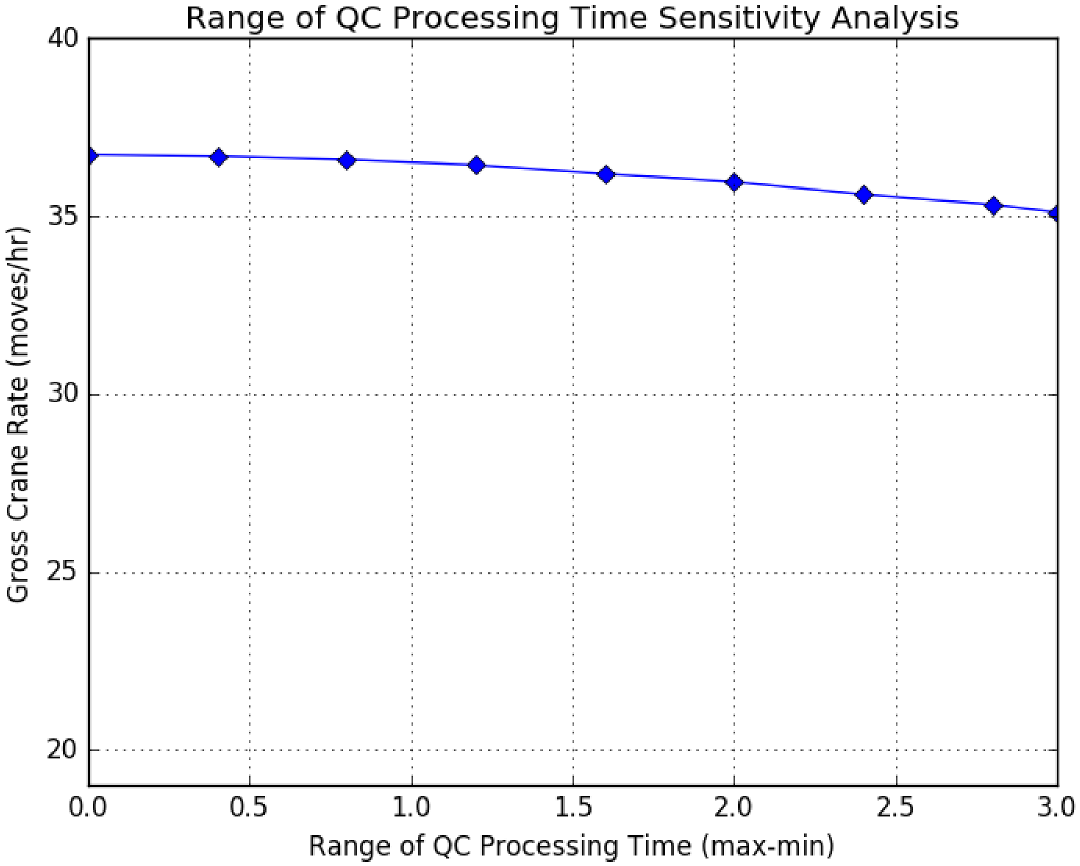
The input parameters for this experiment are presented in Table 5.7. The vehicle fleet size to QC ratio for this experiment is 6. The travel time is a uniform distribution between 120 seconds to 240 seconds. It was designed this way to provide a worst case realistic travel time, while keeping the average at 180 seconds. The yard processing time was not changed. The QC processing time is a triangular distribution with a mode of 1.5 minutes/move. The difference between range (max-min) of the QC processing time starts at 0.0 and is increased to 3.0 in increments of 0.4. The range is increased symmetrically as to not skew the distribution in either direction.

Input Parameters	Values
Number of Vehicles	12
Number of QCs	2
Travel Time	Uniform(120,240) seconds
Yard Processing Time	Triangular(1.2 , 2.0 , 3.4) + Triangular(0.7 , 1.0 , 1.3) minutes

Table 5.7: The input parameters for experiment 2 of varying the range of the QC processing time distribution.

The results are presented in Figure 5.7. As the range increases the gross crane rate decreases. When the range is the smallest at 0.0, the gross crane rate is the largest at 37.0 moves/hour and when the range is the largest at 3.0, the gross crane rate only drops to 35.0 moves/hour. This small drop in the gross crane rate indicates that the vehicle distance threshold is robust to variability in the QC processing time.

Figure 5.7: The effect of increasing QC processing time distribution range (max-min) on gross crane rate.



These two experiments indicate that container terminal operators should pay attention to accurately determining the QC processing time for the vehicle distance threshold as it has a large impact on QC performance, but once determined the QC processing time is robust to the variability that occurs in daily operators.

Yard Equipment Sensitivity Analysis of the Vehicle Distance Threshold

Experiment 1: Increasing Yard Processing Time

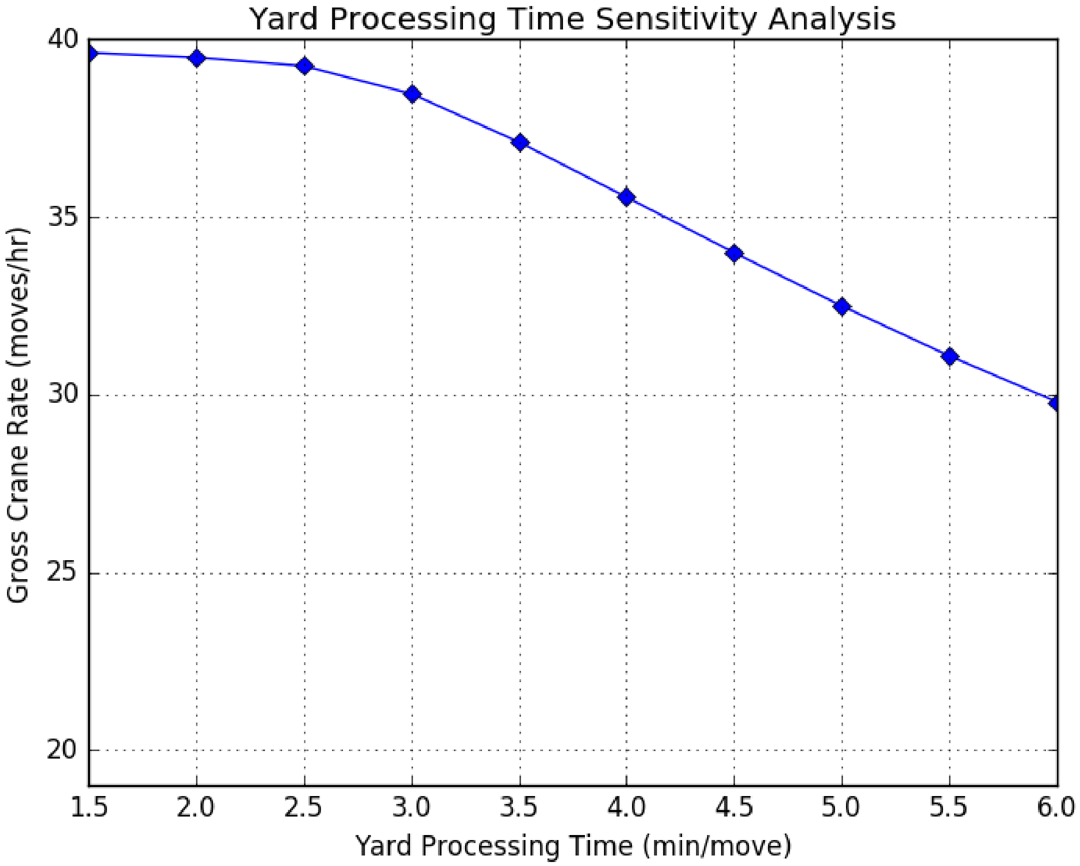
The purpose of this study is to investigate how the vehicle distance threshold responds to increases in yard processing time. The objective of this experiment is to see how large of an affect does the yard processing time have on the gross crane rate of a QC. The input parameters for this experiment are presented in Table 5.8. The vehicle fleet size to QC ratio for this experiment is 6 and the travel time is a uniform distribution between 120 seconds to 240 seconds. The travel time was designed this way to provide a worst case realistic travel time, while keeping the average at 180 seconds. The QC processing time was not changed. The yard processing time is increased from 1.5 minutes/move to 6.0 minutes/move in increments of 0.5 minutes/move.

Input Parameters	Values
Number of Vehicles	12
Number of QCs	2
Travel Time	180 seconds
QC Processing Time	Triangular(1 , 1.5 , 2) minutes

Table 5.8: The input parameters for experiment 1 of varying yard processing time distributions.

The results are presented in Figure 5.8. The gross crane rate remains constant at 39.0 moves/hour when the yard processing time is less than 3.0 minutes/move. As the yard processing time increases greater than 2.5 minutes/move, the gross crane rate decreases linearly to 30 moves/hour. Compared to the QC experiment, the gross crane rate only drops by 9.0 moves/hour while in the QC experiment the gross crane rate dropped by 18.0 moves/hour. This result shows that the QC processing time has a greater impact on the gross crane rate than the yard processing time.

Figure 5.8: The effect of varying yard processing time distribution on gross crane rate.



Experiment 2: Increasing the Range of the Yard Processing Time

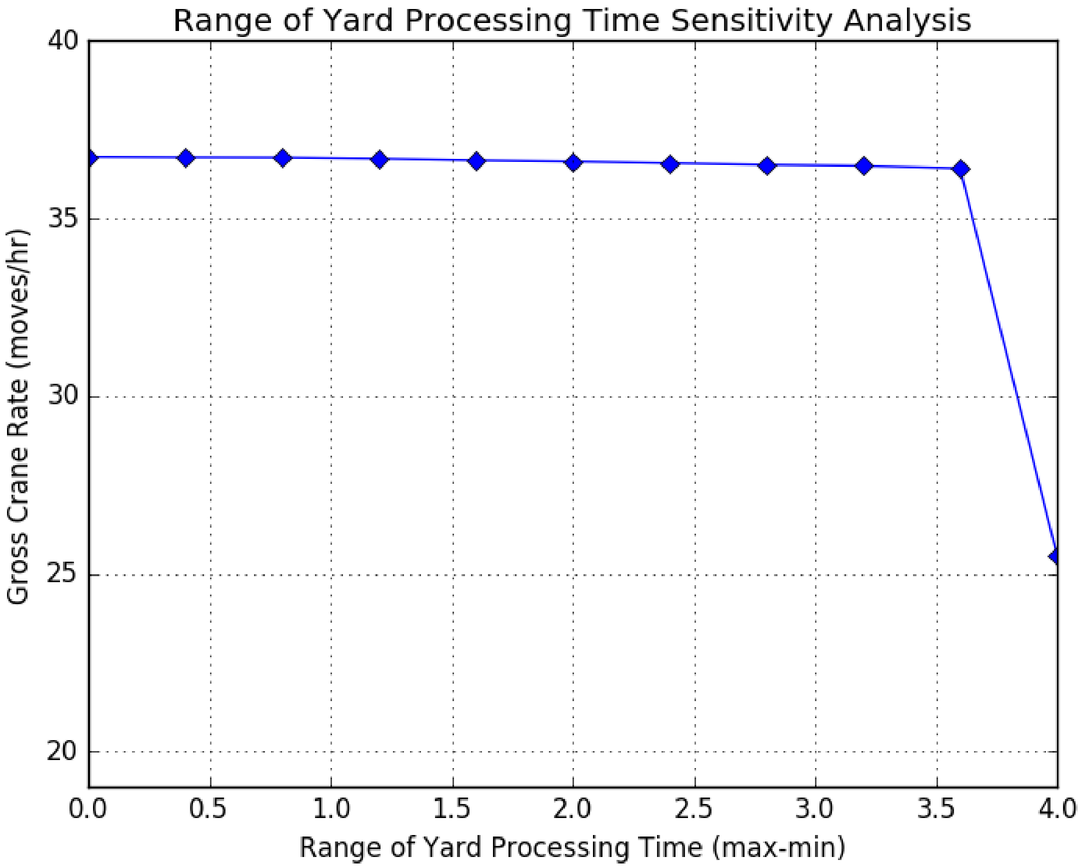
The objective of this experiment is to see how the vehicle distance threshold holds up to variability in the yard processing time. This is important to investigate as the yard processing time is bound to fluctuate during daily operations. The input parameters for this experiment are presented in Table 5.9. The vehicle fleet size to QC ratio for this experiment is 6. The travel time is a uniform distribution between 120 seconds to 240 seconds. It was designed this way to provide a worst case realistic travel time, while keeping the average at 180 seconds. The QC processing time was not changed and the yard processing time is a triangular distribution with a mode of 1.5 minutes/move. The difference between range (max-min) of the yard processing time starts at 0.0 and is increased to 4.0 in increments of 0.4. The range is increased symmetrically around the mode as to not skew the distribution in either direction.

Input Parameters	Values
Number of Vehicles	12
Number of QCs	2
Travel Time	Uniform(120,240) seconds
QC Processing Time	Triangular(1 , 1.5 , 2) minutes

Table 5.9: The input parameters for experiment 2 of varying the range of the yard processing time distribution.

The results are presented in Figure 5.9. As the range increases the gross crane rate decreases. When the range is the smallest at 0.0, the gross crane rate is the largest at 37.0 moves/hour and when the range is increased to 3.6, the gross crane rate only drops below 37.0 moves/hour. As the range increases to 4.0, the gross crane rate drops dramatically to 25 moves/hour. This indicates that the vehicle distance threshold is robust, but eventually the yard processing time becomes the bottleneck and the gross crane rate is effected. In most cases, container terminal operators will not have to worry about variability in daily operations, but a big disruption in the yard will impact QC performance.

Figure 5.9: The effect of increasing yard processing time distribution range (max-min) on gross crane rate.



Chapter 6

VALIDATION

Validation may be defined as "the process of determining the degree to which a simulation model and its associated data are an accurate representation of the real world from the perspective of the intended uses of the model" (DoD, 2016) [14]. A two step validation is done by first checking that the simulation model accurately represents the real system and that the vehicle distance threshold model predicts the performance of the QCs for different numbers of vehicles. To do this, data was obtained from a container terminal and an experiment was set up to compare processing times of QCs for a number of jobs between the simulation model and container terminal data.

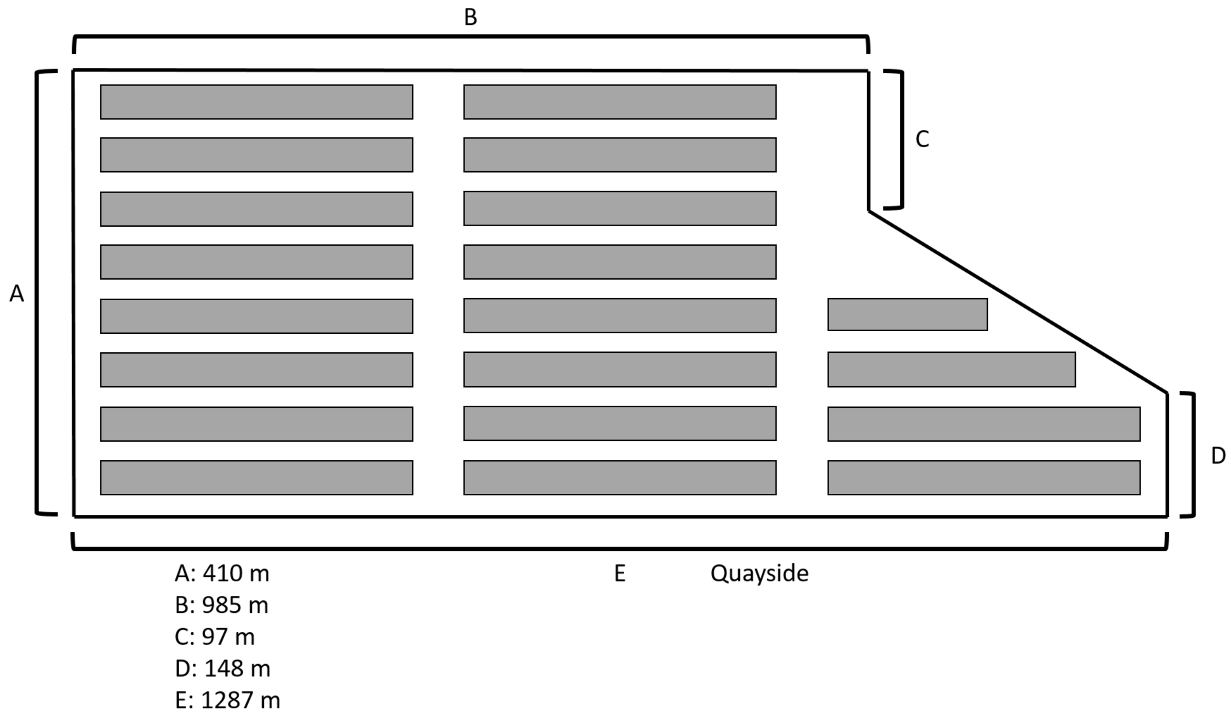
6.1 Experiment Data and Set Up

6.1.1 Data

To validate the vehicle distance threshold model, ideally the data needed would contain the number of moves for a QC, the QC utilization, a constant number of vehicles, and container locations in the yard. This would allow experiments to be set up to apply the vehicle distance threshold to these scenarios to determine if there was an adequate number of vehicles. In some scenarios there would be enough vehicles so that it is not the bottleneck of the system. In other cases the vehicle distance threshold could indicate when the vehicle fleet size is not adequate to process the required set of jobs without causing a delay at the QC. Unfortunately such granular data was not available due to proprietary information and aggregation of data.

The data that was obtained from a container terminal was for a period of 3 days and 14 different vessels. This data contained the pick up times of vehicles at QCs. By processing this data, one could obtain the processing time of a number of jobs for each QC and the number of vehicles working that specific QC. The data had to be cleaned up to control for noise (external factors) such as changes in shifts, unexpected delays, and double container moves. The cleaned data can is presented in Table 6.1. There are 23 data points that were obtained with the number of moves ranging from 8 to 149 and the number of vehicles between 3 to 6. The size of the container terminal yard is presented in Figure 6.1.

Figure 6.1: The dimensions of the container terminal used for validation.



QC ID	Number of moves	Number of vehicles	Completion Time (hrs)
1	51	6	1.6017
2	41	5	1.4342
3	76	5	2.7867
4	18	4	0.8914
5	27	3	1.4647
6	92	5	3.1717
7	39	5	1.2061
8	149	6	4.1914
9	140	6	3.4214
10	96	6	2.4794
11	49	5	1.6122
12	79	5	2.2578
13	20	5	0.6786
14	11	4	0.4178
15	40	6	1.0906
16	40	4	1.5375
17	45	4	1.9503
18	20	3	0.9272
19	30	3	1.0681
20	8	4	0.3122
21	60	5	2.2647
22	47	6	2.9369
23	61	6	2.8603

Table 6.1: Data obtained from a container terminal for different QCs.

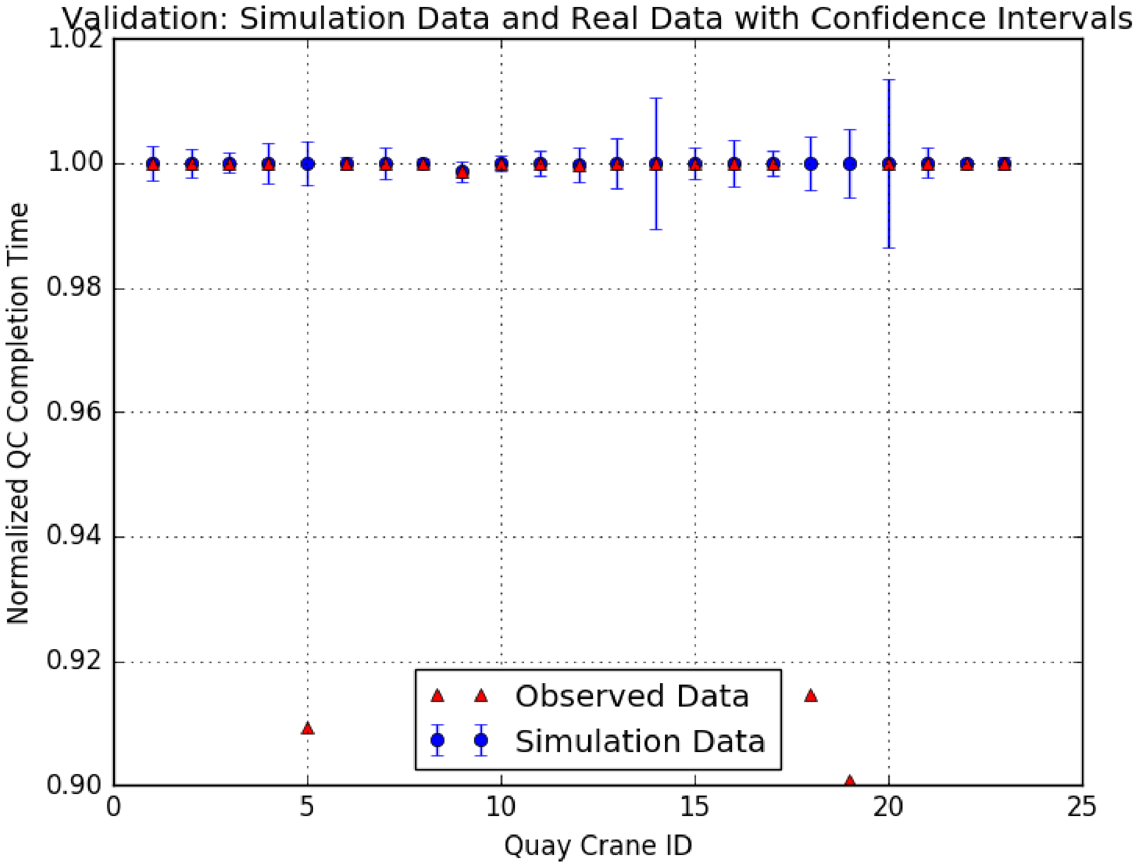
6.1.2 Experiment Set Up and Parameters

An experiment was setup to compare the processing time obtained from the container terminal to the processing time from the simulation model. Due to lack of specific container locations, a travel time distribution was calculated from the container yard map in Figure 6.1. The farthest a vehicle would have to travel to get a container is 1697 m (A+E). Assuming proper planning and container placement, the worst case scenario for travel distance of a vehicle is assumed to be half this distance, 848 m. By using a vehicle speed of 25 km/hr and accounting for external delays in travel such as turns and yard congestion, the worst case expected travel time is calculated to be 180 seconds. The best case travel distance was determined from talking to container terminal operators and was determined no less than 60 seconds. A random policy of container locations in the yard was assumed and the expected travel time distribution of uniform was used. This gave an expected travel time of Uniform(60, 180) seconds. The QC completion time, the number of moves, and the number of vehicles were taken without modification from the data for each run in Table 6.1.

6.2 Results and Analysis

The results from the simulation model for the processing time of the moves for each QC and the processing time for the moves for each QC from the container terminal data were then normalized to 1. The results show that most of the container terminal completion time is within a 95% confidence interval of the mean completion time obtained from the simulation model, the values are presented in Figure 6.2. There were 3 container terminal values that fell outside the 95% confidence interval of the simulation results, these values were for QC 5, 18, and 19. These outliers all occurred for cases where there was a vehicle fleet size of 3. This was due to the lack of specific container location data and the small sample of moves for these specific cases, which were all less than 30. By not having the exact locations of the containers in the yard, all of the travel distance could have been within the vehicle distance threshold, which would allow the completion time seen in the container terminal data to be faster than the simulation results. By discarding the outliers, the data produced by the simulation model is able to represent the real system.

Figure 6.2: Plot of the normalized mean and confidence interval of the results of the simulation and the values from the container terminal.



Chapter 7

DISCUSSION

7.1 Summary

In this thesis the vehicle distance threshold that was developed to provide feedback into quayside operations for container terminals was introduced. A simulation and sensitivity study were conducted to analyze the applicability and the robustness of the vehicle distance threshold to model real container terminal quayside operations. A validation was then completed to show the applicability of the simulation model to represent container terminal quayside operations.

The vehicle distance threshold represents the effective container location distance in which container retrieval will not cause a delay at the quay crane. The simulation studies provides insight into how different vehicle fleet sizes affect container terminal quayside performance, while the sensitivity analysis shows that the vehicle distance threshold is applicable in stochastic situations. Lastly the validation shows the simulation model accurately represents container terminal quayside operations.

The vehicle distance threshold is applicable to all types of container terminals, while being robust in stochastic situations. It provides a feedback loop for container terminal operators to understand container terminal performance under different vehicle fleet sizes.

7.2 Limitations

The vehicle distance threshold is applicable to many container terminal configurations and stochastic scenarios in its current form, the vehicle distance threshold is not readily applicable to container terminals that use a vehicle pooling policy. The pooling of vehicles is important for the future of container terminals, as it allows them to reduce the empty travel time of vehicles by sharing them across all of the quay cranes. How to apply the vehicle distance threshold to the pooling policy of vehicles is an important issue because pooling allows container terminal operators to use a smaller vehicle fleet size to complete the same amount of work.

The vehicle distance threshold provides insight on how container terminals quayside operations will perform, but it does not explain why an issue or delay occurred. Container terminal operators must analyze the results from the vehicle distance threshold along with root cause analysis to fully utilize the tool. This may be difficult for container terminal operators who may have a many competing demands on their time. The vehicle distance threshold requires set up work to be done before it can be properly used. By integrating this into the current terminal operating system, this work could be done by the terminal operating system rather than by the container terminal operator.

7.3 Future Work

Additional investigation should be undertaken to apply the vehicle distance threshold to container terminals that use a vehicle pooling policy. Work can also be done to implement or combine the vehicle distance threshold into information technology systems of container terminals or provide a decision support system around the vehicle distance threshold. This would allow container terminal operators to use the analytical methods without having to have the prior knowledge or having to go through the calculations needed by hand. The vehicle distance threshold can help container terminal operators understand the impact of the decisions they are making and how they effect the performance of quayside operations.

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