ABSTRACT

OPTIMIZING CONTAINER RETRIEVAL OPERATION AT A PORT CONTAINER TERMINAL

by

Dejan Besenski

In the presence of major challenges, where ports are striving to improve their operation and stay competitive in the global market, the issue of port efficiency, particularly the intelligent management of straddle carriers is investigated in this study. A new approach is presented that optimizes container handling equipment operation and is beneficial for the terminal operator in terms of improving productivity, providing faster service and reducing operating cost. Also, the solution provides acceptable service for truckers. The operational strategies presented are able to assess the operation from the truckers' and terminal operators' perspective.

The research is structured into four different scenarios that use an assignment logic and scheduling methodology to describe the continuous time dependable assignment process of straddle carriers to trucks. In doing so it provides the solution to the question that this dissertation poses. The assignment models used in an attempt to answer the research question are stated as follows:

- A model is developed to assign straddle carriers to trucks based on the First Come First Served (FCFS) Rule. This is the baseline model and other algorithms will try to improve upon this solution.
- Two different applications of the Hungarian Algorithm are used for the straddle carrier to truck assignment problem. The first implementation of the Hungarian Algorithm does not consider truck waiting time. The second model implements the truck priority rule into the assignment procedure.

- Finally, a heuristic implementation of the implicit enumeration procedure develops the sequence of jobs assigned to straddle carriers that will minimize the total distance travelled by them.

The concept of a planning period is introduced for models where the Hungarian Algorithm and the Heuristic with Integer Enumeration are used. The planning period is defined as a time interval within which one can find the optimal solution to the straddle assignment problem. The assumption that by introducing a planning period and thus taking advantage of known truck-container pairs provides better allocation of straddle carriers to trucks is investigated and the answers to questions that this dissertation addresses are presented.

An analysis is presented that utilizes the knowledge of the truck arrival rate to determine the optimal straddle carrier fleet size and the duration of the planning period. The results can be used by port terminal management to develop an optimal straddle carrier deployment strategy and planning period that will minimize the total cost of operation.

The framework is designed to answer questions of interest to port terminal management, and to investigate the trade-off between the cost of operation and the service provided to trucks. The analysis presents guidelines for pricing strategy if an appointment system is implemented.

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Dejan Besenski

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APPROVAL PAGE

OPTIMIZING CONTAINER RETRIEVAL OPERATION AT A PORT CONTAINER TERMINAL

Dejan Besenski

12/18/08

Dr. Lazar N. Spasovic, Dissertation Advisor
Date
Professor of Civil and Environmental Engineering, NJIT

12/18/08

Dr. Athanassios Bladikas, Committee Member
Date
Associate Professor of Industrial and Manufacturing Engineering, NJIT

12/18/08

Dr. Steven I-Jy Chien, Committee Member
Date
Professor of Civil and Environmental Engineering, NJIT

12/18/08

Dr. Janice R. Daniel, Committee Member
Date
Associate Professor of Civil and Environmental Engineering, NJIT

12/18/08

Dr. Sanchoy K. Das, Committee Member
Date
Professor of Industrial and Manufacturing Engineering, NJIT

BIOGRAPHICAL SKETCH

Author:	Dejan Besenski
Degree:	Doctor of Philosophy
Date:	January 2009

Undergraduate and Graduate Education:

- Doctor of Philosophy in Transportation Engineering
  New Jersey Institute of Technology, Newark, NJ, 2009
- Diploma in Transportation Engineering,
  Belgrade University, Serbia, 2003

Major: Transportation

Presentation and Publication:

Steven Chien, Lazar Spasovic, Kier Opie, Vivek Korikanthimath, Dejan Besenski, "Simulation-Based Analysis for Toll Plazas with Multiple Toll Collection Methods," The 84th TRB Annual Meeting, Washington DC, January 2005

This dissertation is dedicated to my family

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CHAPTER 1

INTRODUCTION

1.1 The Purpose of the Dissertation

The purpose of this document is to present methods for improving the productivity and the service quality of straddle carrier operations at a port terminal. The straddle carrier is a machine that straddles a truck-tractor and removes a loaded export container from the truck-tractor's chassis and delivers it to the yard for subsequent loading on the ship for an outbound voyage by sea. In the opposite direction, it receives a loaded import container and delivers it to the trucks or rail for the outbound movement by land. The operation is dynamic since the straddles that need to be assigned to containers in real time and their workload is determined by the arrival rates and flows of containers. For this reason, it is imperative to determine the optimal container handling procedure using the real time information regarding equipment position and truck arrivals.

The dissertation presents a model for optimizing the straddle carrier fleet size, and planning period . The results and suggestions for improving operations are presented. The model developed will allow terminal operator to operate efficiently and to reduce the cost of operation. The importance of this problem lies in a need to improve daily operations at the terminal and to meet service requests from its customers.

1.2 Organization of the Dissertation

The organization of this dissertation is as follows. Chapter 2 provides the reader with background information on the global trends in container traffic. An understanding of the causes and magnitude of this trend is needed to put the research into a larger perspective.

The container terminal structure, basic elements and operation is presented in Chapter 3. The problem specific to the land side operation of the container terminal and the role of straddle carriers in the port system is presented in Chapter 4. The formulation of the problem that this dissertation answers and research questions are presented in Chapter 4. Chapter 5 presents the literature review that addresses the previous work done in developing efficient equipment operations in terminals. Also, the research in developing simulation models of the port operation is presented and analyzed. Chapter 6 presents the methodology and heuristics used to solve the problem. The results and the analysis of the results are discussed in Chapter 7. The analysis of how the straddle carrier fleet size and the duration of the planning period are impacted by different truck arrival rates is presented in Chapter 8. Chapter 9 discussed trade-offs between the cost of operation and service quality. The operation with variable straddle carrier fleet size and planning period is presented and the results are compared to the operation with fixed straddle carrier fleet size. The pricing structure of an appointment system is discussed and its implication on rates that operator should charge is presented. Chapter 10 presents the conclusion and suggestions for future research.

CHAPTER 2

BACKGROUND

A container port provides an interface between ships, railroads and trucks and represents a critical link in the intermodal[1] chain. In the last few years, increased international trade resulted in unprecedented growth in containerized freight volumes handled by port terminals worldwide. The increase in container volume puts pressure on port management to accommodate new requests from clients for fast, timely and efficient service.

Also, rising competition among ports and the introduction of high capacity ships in operation has put enormous pressures on port management to develop efficient container handling process. To further increase capacity of the terminal and speed up the transshipment processes, a change in container handling operational practices was necessary and this led to the modification of terminal layouts as well as systems design.

The growth of containerized cargo increased the demand on the land area at terminals for storing containers. Often, there is congestion at the land access side of the port terminal and on the highway network in the port terminal vicinity. Due to large truck queues some large container terminals have to pay truckers for their excessive waiting time.

Since the market requires ports to increase their throughput and because many ports are working at, or close to, capacity, new methods and tools are needed that enable terminal operators to better synchronize activities within the terminal. Either new efficient equipment needs to be deployed or new operational methods need to be put in practice or a combination of both to assure efficient terminal operation. This is important because the competition between terminal operators and better service can attract shippers to take their business to a different terminal.

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[1] Intermodal - being or involving transportation by more than one form of carrier during a single journey

2.1 Increasing Trends in Global Container Traffic

The total container traffic volume of the top container ports, with volume of more than one million TEUs[2], reached 297 million TEU in 2005, a 10.9 per cent increase compared to 2004. The analysis that has been done by the ISL (Institute of Shipping Economics and Logistics 2005) included 77 ports (38 Asian/Oceania ports, 19 European ports, 18 American ports and 2 ports located in Africa). In 2005, approximately 65% of the world container traffic, in terms of TEU, was attributed to Asian ports, whereby the top eight Chinese ports alone represented 26.5% of the total container traffic. Europe's share was 18.5% of the world container port traffic and America's 15.2%. The top Chinese mainland container ports (without Hong Kong) grew on average by more than 25% per year. Their annual container traffic was 13.4 million TEU in 1999 and 58.5 mill TEU in 2005, respectively.

The containerized traffic in the U.S. ports is increasing rapidly every year, especially the traffic to the US West Coast ports. The 10 U.S. ports handled 85 percent of the U.S. containerized traffic in 2005 (Bureau of Transportation Statistics). Figure 2.1 shows the increasing trend in growth of container traffic in the US ports between 1996 and 2005, the last 10year period for which volume data are available.

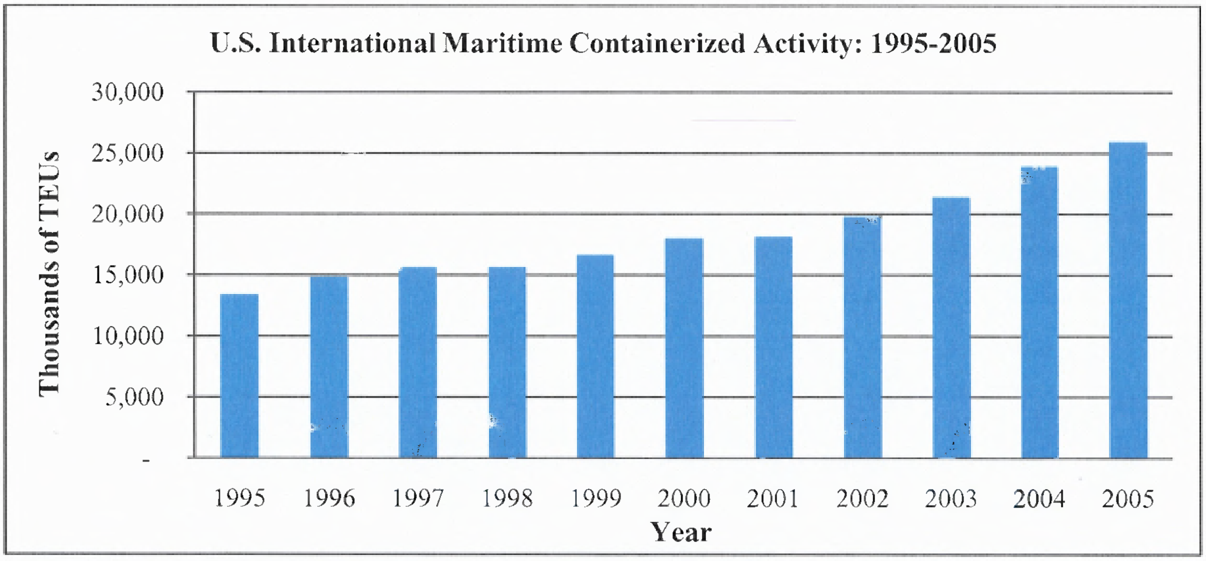

Figure 2.1 Annual container traffic of U.S. Ports 1996-2005 (TEU)

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[2] TEU – twenty foot equivalent unit, a measure used in intermodal transport

North American Pacific (West Coast) ports have strong relationships with the Asian ports. Their traffic is more than 90 percent distributed to and from the Far East. This interrelation is underlined by the analysis of monthly container traffic of North American West Coast ports done by the ISL and demonstrates an increasing trend in container traffic going through major U.S. Ports.

For the North American East Coast ports the Asian market is of significant importance. The ports of New York/New Jersey's top trading partners are located in Asia. About 50 per cent of the ports container traffic in 2005 was related to the trade with Asia and every year the container volume that goes through the ports of New York/New Jersey is increasing. The trend is shown in Figure 2.2.

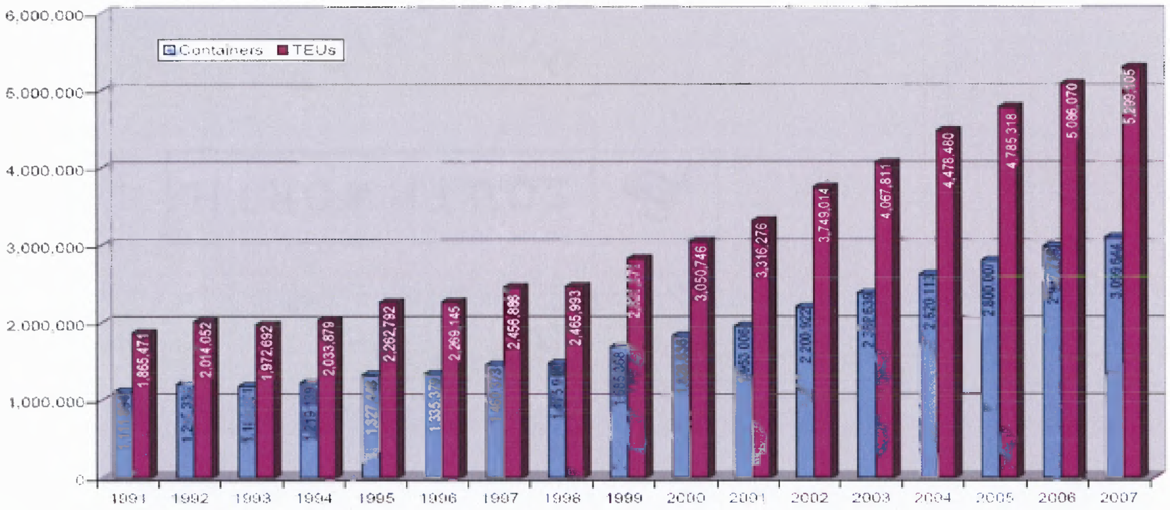


Figure 2.2 Port of NY/NJ total containers and TEU's 1991-2007

Table 2.1 show that the containerized cargo volumes in the Port of New York and New Jersey rose nearly 7% from 2005 to 2006. This is followed by a continued growth in trade with the Far East, North Europe and Southeast Asia. ExpressRail, the Port Authority's on-dock rail terminals in New Jersey, set a new record in 2006, handling 338,882 containers, 11.8 percent more than in 2005 (Port Authority of New York and New Jersey). In the next 10 years, nearly $2 billion in infrastructure upgrades are planned for the Port Authority's marine terminal facilities and for off-port roads and railways to improve the flow of cargo.

Table 2.1 Trends in Container Volume at the Port of New York/New Jersey

Container Trade	2005	2006	% Change Over 2005
Loaded Import TEUs*	2,408,121	2,599,554	7.9%
Loaded Export TEUs*	976,882	1,051,372	7.6%
Total, Loaded TEUs	3,385,003	3,650,926	7.9%
Total TEUs (loads and empties)**	4,785,318	5,092,806	6.4%
Total Containers (loads and empties)**	2,800,007	2,991,086	6.8%

Source: Journal of Commerce – PIERS , Port Authority of New York & New Jersey Facility Counts

The Tri-State Transportation Campaign predicts that freight tonnage moving through New Jersey transported by truck will increase to 77% by 2020. The PANYNJ statistics show that 88% of the cargo transported to and from the port terminals is by truck (Port Authority of New York and New Jersey).

The data indicate that the increasing container traffic puts pressure on container terminal management to review their operational practices, and make any changes needed so that they can continue to provide adequate service to their customers.

2.2 Economics of Port Operation

Port terminal operators have to consider the following costs:

- Land Lease Cost: A port terminal operator is usually leasing the land for a port terminal from a public entity. For example, terminal operators at the Port of New York/New Jersey are leasing the land from the Port Authority of New York and New Jersey, a bi-state public agency entrusted with managing port and airport facilities in the New York metropolitan region.
- Capital costs: The port terminal is buying terminal infrastructure and cargo handling equipment such as truck gate equipment, cranes, straddle carriers, top loaders, etc.

- Operating expenses: included here are costs of labor, utilities, and equipment usage and maintenance.
- Overhead expenses such as insurance, marketing etc.

The above costs determine the unit cost per container that the terminal operator uses to determine the rates/fees that charge to clients, usually steamship lines. The capital, lease and part of the overhead cost can be considered fixed costs (i.e. they are independent of the container volume handled by the terminal). However, they need to be allocated to the containers passing through the terminal. A higher throughput would translate into a lower allocated unit cost (per container) associated with these cost categories. On the other hand, the maximum terminal throughput is determined by the terminal capacity and is subject to the characteristics of terminal design, container handling equipment, work flow and operating practices designed to handle containers, as well as the required level of service parameters. To increase the capacity and allow higher throughput the terminal operator has to either purchase new equipment, change/improve work flow, or relax the level of service requirements. Purchasing or leasing new equipment will result in higher unit cost. Reducing the level of service may result in customer dissatisfaction eventually causing some of them to stop using the terminal. Therefore, the most cost-effective measure a terminal can take to increase capacity for a given equipment pool and level of service requirements, is to reevaluate the terminal operations and work processes and seek improvements by developing a new strategy or methodology of handling containers. Chapter 8 will demonstrate that this is true.

2.3 Port Investments

Table 2.2 shows the cost of planned capital improvements that will be implemented in Ports of New York & New Jersey to accommodate anticipated growth in container demand. The table shows that approximately one third of the investments will be used to accommodate larger ships and maintain the channel; the reminder of the budget would be used for port infrastructure improvements and terminal development.

Table 2.2 Planned Capital investments in the Port of New York and New Jersey from 2007-2016

Program	$ Millions
Channel Deepening	679
Marine Terminal Development and Redevelopment	418
Port Roadway Improvements and Safety	367
Rail Cargo Infrastructure	300
State of Good Repair	195
Security	24
Total	1,983

Source: Port Authority of New York and New Jersey Trade Statistics

Since the operations of a container port are influenced by a large number of interacting factors (personnel, varying ship and truck arrival patterns, various kinds of cargo-handling equipment), optimization of such a complex system is a challenging task. Communication with external parties, such as shipping lines, agents, truck and rail companies, which provide port management with information necessary to better plan their operation activities, is crucial in developing a proper operations plan for the port.

CHAPTER 3

DESCRIPTION OF A PORT CONTAINER TERMINAL OPERATION

In Chapter 2 the growth trends in container traffic were described and the costs that a port terminal faces when establishing an operation were identified. This chapter presents the port container terminal structure used in this dissertation. Although the equipment and layout vary from port to port what is presented here is rather typical. The container handling processes that occur in the terminal are identified and described and the role of straddle carrier as a container handling equipment is explained.

3.1 Terminal Description

A port serves as an interface between ocean and land transport modes and a temporary storage facility for containers moved by these modes. In general terms, a container terminal can be described as a system that congregates two interfaces, the landside and dockside interface. The landside interface, shown in Figure 3.1, provides service to trucks and trains where dedicated handling equipment transport containers between the truck and train area and the container yard. The dockside area provides service to ships (unloading and loading of containers to and from the vessel) and a flow of containers between the container yard and docks. The yard area is separated into different stacks (or blocks). The stacks are separated into sections for import, export, special and empty containers.

There may be a section for handling special containers. Special containers are those that transport hazardous materials or are refrigerated (called often reefers). The reefers require electric service while they are in the yard and there is a need for a special section for these containers.

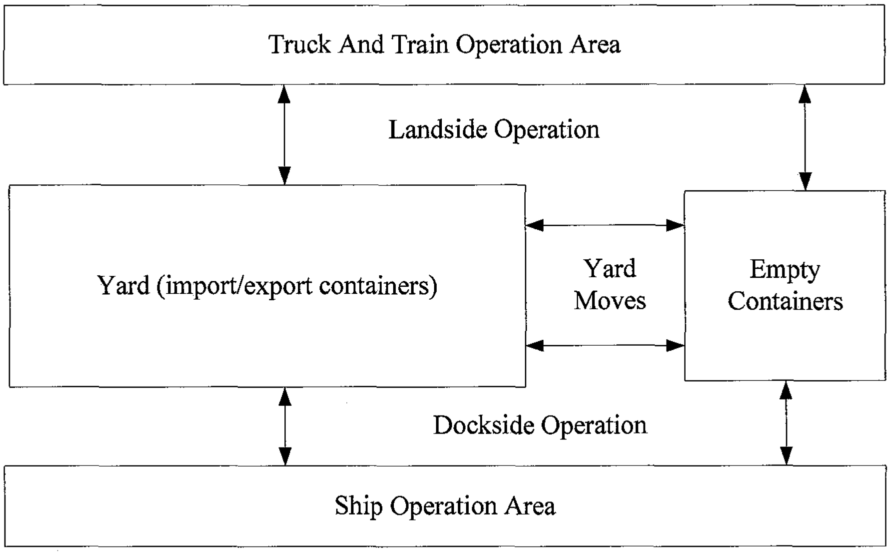


Figure 3.1 Terminal interfaces

At a typical marine container terminal there are four basic logistics functions that are performed: receiving, storage, staging, and loading. Receiving involves taking custody of export or outbound containers from customers (called shippers) for the subsequent loading of these into vessels. The outbound containers are brought in by truck or on-dock rail. Inbound containers (or imports) are unloaded from vessels to be picked up by receivers (called consignees). The inbound containers are picked up by trucks or delivered to the on-dock rail facility for a further line haul movement by rail. Storage is the function of placing a container on the terminal in a known and recorded location so that it can be easily retrieved. Staging is a function of preparing a container to leave the terminal. The loading function involves placing a container on a ship, a truck, or on-dock rail.

3.2 Landside Area Functions

3.2.1 Operations at the Gate

The processes occurring at the land side area are comprised of interdependent operations ranging from container arrivals by truck (or train) and various related container handling operations performed by yard equipment. Containers arriving by trucks are entering thru the gate, shown in Figure 3.2, and their check-in is usually a multistage process.

Figure 3.2 Gate entrance at the container terminal

The first step is the screening and approval of truck drivers to enter the gate. At the gate, the truck driver information, company and purpose are verified by the gate operator. The gate operator records the container information, inspects the truck and container by camera and after the identification process is completed the truck is directed to proceed to a slot location where it will be processed by yard equipment. The container information associated with the truck arrival is retrieved from the data base and passed on to the scheduling routine that assigns the yard equipment to service this transaction. Participants in the port operation utilize the EDI (electronic data interchange), which allows the electronic exchange of information among terminal clients, truckers, and other parties.

3.2.2 Truck Service by Yard Equipment

The arriving truck has been assigned a designated slot in the parking area of the yard and a particular piece of yard equipment called straddle carrier is assigned to it. For the trucks delivering an export (outbound) container, the straddle carrier removes the container from a truck-tractor chassis. It does that by straddling the chassis and lifting the container using an overhead crane. The straddle then drives away carrying the container in its belly. If the truck is picking up an import container, the straddle carrier locates the container in the yard and transports it to the truck slotting area and loads it on the truck's chassis. A snapshot of the operation is presented in Figure 3.3. In this figure, the straddle at the left of the truck slotting area have just removed a container from the truck while the straddle in the lower right has just delivered the container to the truck.

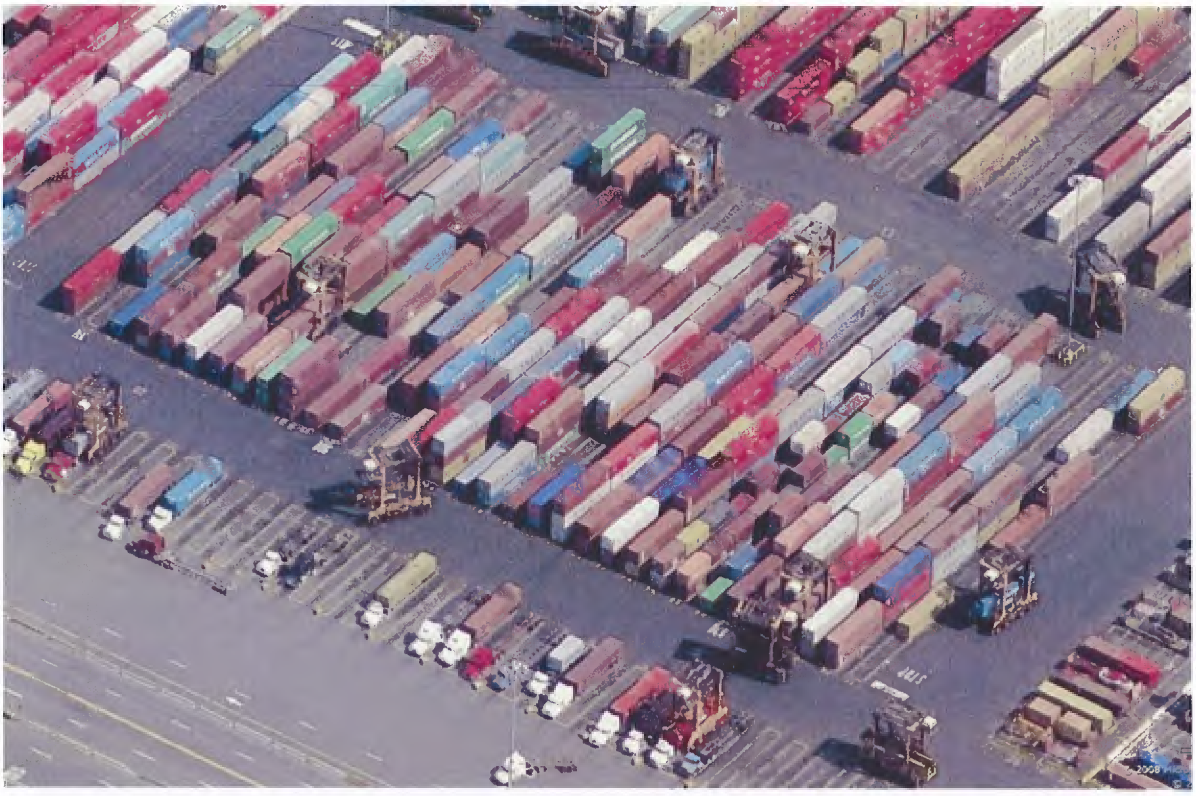


Figure 3.3 Truck slot area being serviced by straddle carriers

The container location in the yard is given by block, row, and tier within the block and is assigned to a straddle carrier in real time upon arrival of the container at the terminal. In some container terminals trucks are directed to park next to the stack where the container they are carrying has to be unloaded from (loaded to). Usually rubber tired gantry cranes (RTGC) are engaged for this type of operation.

3.3 Dockside Area Functions

When a ship arrives, the unloading is performed by cranes as shown in Figure 3.4. The cranes unload containers in the area next to them where the containers are then picked up by straddle carriers or RTG cranes and then delivered to the storage yard. In some terminals containers are loaded directly to Automated Guided Vehicles (AGV's) or the terminal's internal trucks that are used as a transportation link between the yard and the dock cranes. Containers are then unloaded and transferred to their designated position in the stack by straddle carriers or yard cranes. Customs inspection for import containers is required and it may occur on dock or some other designated location.

Figure 3.4 Dock crane operation at the berth

The import and export stacks of containers are usually separated in the yard so that different tasks related to those containers can be performed. This separation may alleviate yard operation congestion. The outbound containers that are picked up from the yard block, are transported to the berth and dropped off at a stacking position that is pre-defined in the stowage plan so that they can be picked by the dock cranes to be loaded onto the vessel. The stowage plan provides information for the retrieval and movement of the export containers to the berth for loading.

CHAPTER 4

STRADDLE CARRIER PROBLEM DESCRIPTION

Chapter 3 presented a description of a typical container terminal operation. The container handling processes were identified for each of the terminal sections. This chapter analyzes the landside operation, particularly the service that has to be provided to trucks arriving at the port to deliver export and pick up import containers. The expectations from truckers and operators in terms of service quality are described. The chapter concludes with a definition of the research objective. The questions to which this dissertation will give an answer are identified as well.

4.1 Introduction

The arrival of truck-tractors with containers is a random process. In addition to the uncertainties related to the arrivals, high-priority or time-sensitive truck requests arise during the operation and without advanced warning. This complexity makes the need for a dynamic decision-making even more apparent at the operational level. By recognizing these uncertainties and utilizing real-time information on truck service expectations, the port operator can develop an optimal straddle carrier dispatching strategy that can lead toward higher profitability while delivering superior service to trucks.

At the operational level, the important decision is about the optimal location where container needs to be discharged from the ship/truck/train and how the container handling equipment (berth cranes, yard cranes, straddle carriers, AGV's etc.) need to be routed in this complex network to maximize productivity. The corollary question is what are the effective methods to control the equipment and ensure that a desired result is achieved.

Container terminal operations need to be optimized in real-time because most of the processes that occur cannot be foreseen in advance. The data regarding delivery of containers to the terminal by truck maybe known from the EDI. However, the exact time when a container will arrive at the terminal is unknown.

As trucks have to travel to transition points where containers are picked by straddle carriers or cranes, the truck sequences at the gate and at the transition point does not have to be the same, since the processing time of the truck at the gate is different for each truck.

4.2 The Straddle Carrier to Truck Assignment Problem

The terminal operator's most important concern is to increase the equipment productivity. This translates into minimizing straddle idle and unproductive time. Therefore, the operator wishes to deploy the necessary straddle carrier fleet that will have a minimum amount of unproductive (empty) moves while providing acceptable truck service in terms of waiting time. Since the position of the container and truck in the yard is known, the loaded travel distance between container and truck can be easily calculated and it's fixed for that trip. What is not known is the unproductive empty travel distance in support of the loaded move. By reducing this empty travel, the utilization of the straddle carrier is increased and wear and tear is reduced.

Truck waiting time is defined as the time period from the moment a truck enters the slot and the time it begins to be serviced by a straddle carrier. This time is of concern for every terminal operator because if this time is reduced, the customer satisfaction is increased. Thus, it is imperative for the terminal operator to improve productivity of its operation (and minimize its cost) while being cognizant of the customer expectations in terms of truck wait time as a measure of service quality.

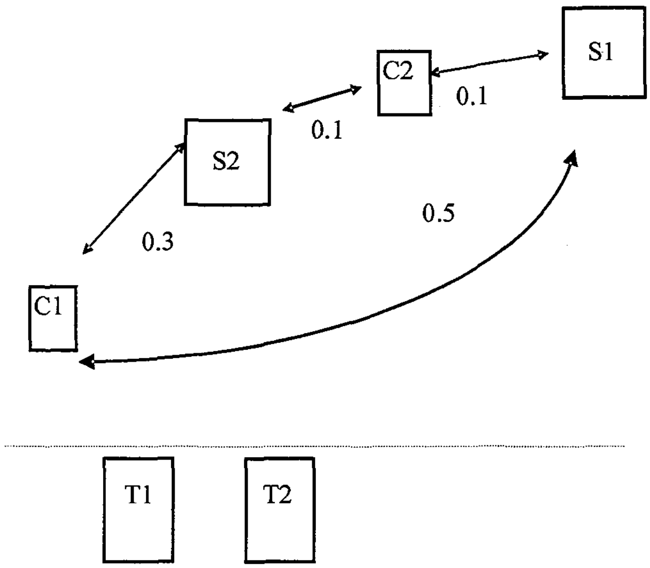
The objective of the terminal operator of improving productivity is accomplished by minimizing the empty travel of straddle carriers, and at the same time improving customer service by minimizing delays. Empty travel is defined as a movement of straddle carrier with no container on board. The delay in customer service is commonly measured by the length of time that arriving truck waits in the slot before it is serviced. In addition to the terminal scheduler's objectives, management would also like to minimize the straddle carrier fleet size in operation. This will reduce the capital cost of straddle carriers, and the annual fixed and variable costs that occur from the use of equipment.

On the other hand, shippers want to minimize the transit time, and they would like that the truck service time in port is faster so that they can reduce inventory cost. The shipper's decision of whether to continue to use the terminal is based on the service quality received from the terminal operator. If the service time is unsatisfactory, the shipper can change the terminal. The truckers would like to be serviced faster, since they are paid by the load and not by the hour.

4.3 Research Motivation

4.3.1 Potential for Reduction in Operating Cost and Truck Service Time

The following two examples are developed by Spasovic and Sideris (1992) to demonstrate that an intelligent assignment could decrease the operator's cost as well as improve customer service. The example of the operation, shown in Figure 4.1, consists of two containers that have to be delivered from the yard to the trucks in the slotting area. The assumptions made are that truck 1 (T1) arrived and was slotted at 8:00 a.m. while truck 2 (T2) arrived one minute later. Truck 1 is picking up container 1 (C1), while truck 2 needs to pick up container 2 (C2). There are two straddle carriers that are in operation and Straddle 1 (S1) is available for the new assignment, while straddle 2 (S2) will be available for a new assignment in one minute. If the straddles are assigned using first-come-first-served (or the closest container) rule, straddle 1 will be assigned to process container 1 while straddle 2 will be assigned to process container 2. The average speed of the straddle carrier is assumed to be 10 mph, the total distance and time that a straddle carrier needs to traverse to reach a container is 0.6 miles and 216 sec respectively (Table of Figure 4.1). If the assignment decision was postponed for 1 minute and then both straddles assigned at the same time with the objective of minimizing the total distance travelled, a better solution would have been obtained. The solution assigns straddle 1 to move container 2 and straddle 2 to move container 1. The result of the assignment, shown in the table of Figure 4.1, demonstrated that empty travel distance decreased by 33% (from 0.6 miles to 0.4 miles) and truck service time decreased by 6% (from 216 to 204 seconds). This shows that straddle carriers can be used more efficiently and at the same time improvements in productivity and service quality can be achieved.

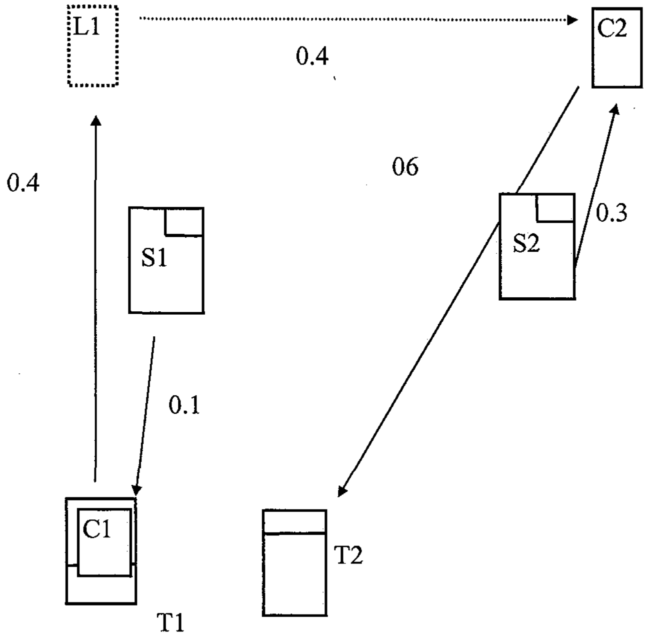


	Assignment	
	First Come - First Served	Optimal Distance and Time
	S1-C1 and S2-C2	S1-C2 and S2 -C1
Distance (miles)	0.5 + 0.1 = 0.6	0.3 + 0.1 = 0.4
Time (sec)	180 + 36 = 216	108 + 36 + 60 = 204

Figure 4.1 Minimizing the combination of empty straddle distance and truck service time

4.3.2 The Trade-Off Between Operator Cost and Truck Service

The example in Figure 4.2 demonstrated how intelligent assignment may further reduce the operator's cost while the customer service time may remain the same or slightly worse. The container C1 needs to be unloaded from the truck and delivered to the yard location L1. Three minutes later a truck (T2) is slotted and container C2 has to be loaded to a truck chassis from the yard. If both straddle carriers are used in processing these two service requests then the solution is in the left column in table on Figure 4.2. If we were to use only one straddle carrier to process both trucks, then the assignment solution is S1-C1 and S1-C2. By eliminating one straddle from the operation the marginal increase in the truck service time of 36 sec occurred. Decreasing the number of straddle carriers in operation results in a substantial reduction in the operator's ownership and maintenance cost.



	Assignment	
	Fleet with 2 straddles	Fleet with 1 straddle
	S1-C1 and S2-C2	S1-C1 and S1-C2
Distance (miles)	01+03 = 0.4	0.1+0.4= 0.5
Time (sec)	144	36+144=180

Figure 4.2 Minimizing the straddle carrier fleet size

Morlok et al. (1995) conducted a study on improving the highway operation (called drayage) of the rail-truck intermodal transportation service. The rail-truck intermodal service consists of truck operations that transport a load from the terminal to consignees and from shippers to the terminal. The rail operation is used to transport trailers with containers between intermodal terminals. The study presents the methodology of reorganizing drayage operation with the goal of improving service quality and reducing the cost of service at the same time.

4.3.3 Drayage Operation

A truck with an empty trailer or container is dispatched from the intermodal terminal to a shippers' location to pick up a load. Two scenarios are possible in this case, the first is that a truck is going to wait with a trailer until it is loaded and then return the trailer to the terminal for the rail movement. In the second scenario the truck will leave the trailer for loading and return to the terminal without the trailer. Other types of operations conducted are the delivery of cargo to consignees and repositioning of empty trailers.

One of the reasons why intermodal service does not have higher share of the long haul service is because the drayage service is allocated among many independent truckers, and each of them is controlling and scheduling their operation independently of one another. This results in many unnecessary non-revenue movements. Thus, the idea was to observe a drayage operation as a system, and planning it to meet the demand and service quality at a minimum cost.

4.3.3.1 Service Improvement and Modeling

Service quality can be improved by scheduling truck moves in advance. The delivery to consignees is performed within few hours of the cargo being removed from the train, and cargo pick-up requests are given to drayage companies at least one or more days in advance. The idea is to pair moves and reduce the empty mileage of trucks. Increasing the load density could result in decreasing non-revenue truck miles and thus cost. By pairing movements, fewer trucks are needed to process service requests and decrease of the cost per load is possible.

A mathematical model for drayage was developed and it was used to evaluate the cost of operation when truck movements are centrally planned. The model's objective was to minimize total drayage and operating cost by selecting trailer movement times and locations and assigning trucks to those movements. The constraints are that all inbound trailers from the terminal to consignees have to be delivered within specific time constraint, empty trailers to shipper has to be delivered for loading and then picked-up within a specific time period and repositioning of trailers to avoid their accumulation has to be performed.

The results showed that improvements in operation are possible and cost reduction can be achieved at the same time. Also, an important finding was that the higher load density is, there are more opportunities for task pairing and thus using fewer trucks for efficient operation. The breakeven distance where intermodal service is competitive to truck service is also reduced. The reorganization and better use of information clearly provided for an efficient scheduling and pricing of drayage service.

4.3.3.2 Conclusion

The question is how the methodology developed for drayage operation presented above can be applied in this case. In case of intermodal service the data was available for the whole day and only a small portion of drayage requests for service was unknown. The information about future events enabled better planning and efficient drayage operation. In the case of truck service in the port, the arrival rate is much higher and it would be possible for the terminal operator to wait for a long time to gather the information related with each truck service request.

4.4 Understanding the Notion of Optimality in a Real Time Solution

Since the truck arrival time at a container terminal is an unknown variable, trucks tend to be processed in the order of arrival. There have been attempts to introduce appointments (a reserved time for trucks calling at the terminal) so that the terminal can better develop its container handling operation strategy, but so far the truck arrival is still random. A real time process of straddle carrier operation is illustrated in Figure 4.3. In this operation, straddle carrier SC1 is dispatched to bring a container for Truck 1 as soon as Truck 1 enters the truck slot area. SC1 delivers the container to Truck 1, and while Truck 1 is leaving the slot, SC1 is repositioned to serve Truck 2, which had brought an export container to the terminal. SC1 removes (or strips in the port terminal parlance) the container from Truck 2 and delivers it to a parking spot in the yard. SC1 then returns empty to the truck slot area and removes the loaded container from Truck 4.

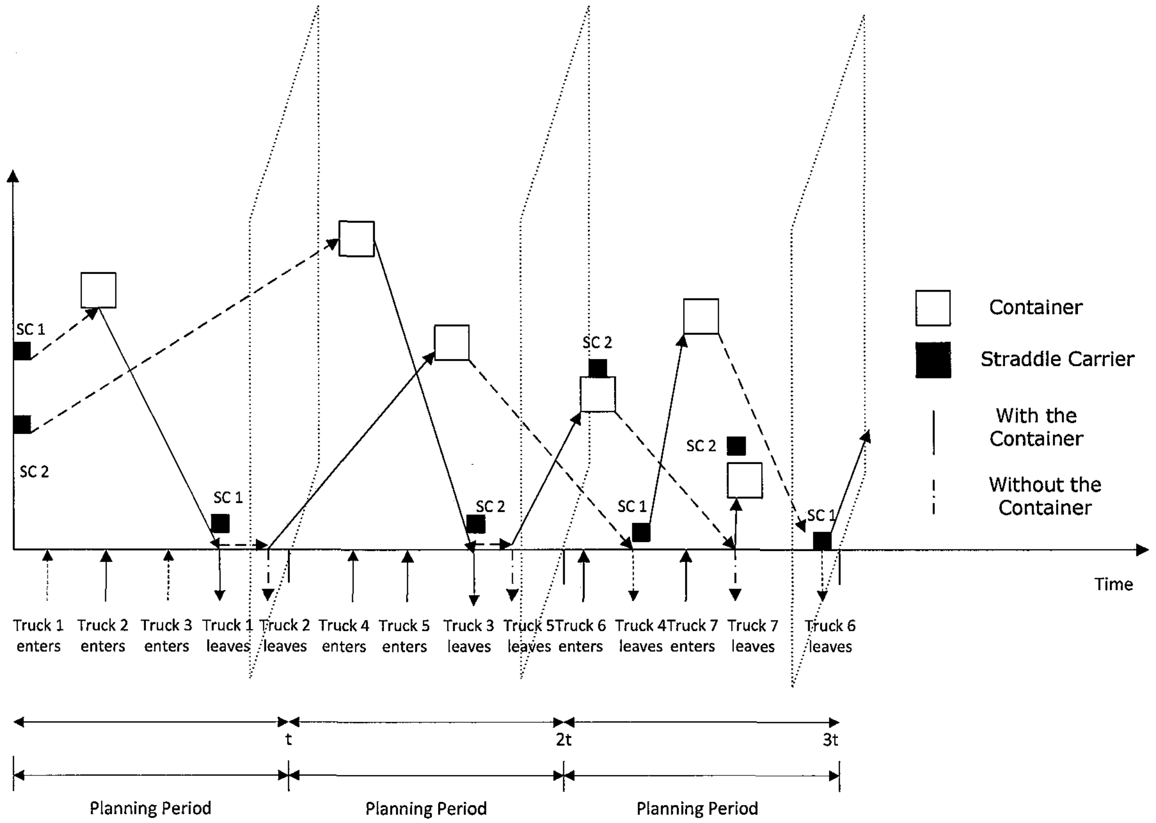


Figure 4.3 Example of straddle carrier operation in time

By observing the operation one can arrive to the following conclusions about the optimality of the assignment of straddle carriers to trucks:

- Since the arrival times of trucks during the day, and the locations of containers (associated with the trucks) in the yard are known, one can develop an optimal solution to the straddle carrier assignment problem. This solution will have optimal job sequence for straddles in terms of the work each straddle needs to perform. While this solution would be optimal in terms of minimizing straddle empty mileage and truck wait time, it is impossible to implement it in the real world, because it would involve "freezing the operation in time" until an optimal "static" assignment can be made. This optimal static operation would give a theoretical lower bound on costs.
- The exact opposite of the above would be to make the optimal assignment each time a straddle becomes available. Under this assignment, the straddle would be assigned to the

closest truck or the one that has waited the longest or a weighted combination of those two objectives. While this assignment may be the best in that particular moment, the operating strategy that consists of a set of these assignments will not lead to the overall optimal solution for the entire operating day. The immediacy of these assignments (while optimal at that moment) will not consider the optimal assignment potential that arises from postponing the schedule until a better assignment can be made as discussed above in Sections 4.3.1 and 4.3.2.

- Therefore, it is prudent to introduce a concept of a planning period – a time interval within which one can find the optimal solution to the straddle assignment problem. This concept would mean that one would allow truck arrivals and service requests to accumulate during a time interval of certain duration and at the end of that period an optimal straddle assignment will be developed. For example, given events and locations up to time t, the optimal schedule would be implemented at time t (or t+1). Then, the issue would be to vary the length of this planning period to find the one that yields the best optimal solution for the entire day's operation. By varying the length of the planning period, one can explore the potential that matching opportunities may yield in improving the overall optimal solution for the day's operation. Once the "optimal duration of the planning horizon" has been determined, then this planning horizon can be implemented in all situations with similar arrival patterns.

Underlying Principle Behind the Planning Period

It is worth investigating length of the time window (called planning period) that will give enough information about truck service requests, to enable terminal operator to efficiently plan operations. For example, instead of processing one service request at a time, maybe the knowledge about the next ten events will give the opportunity to better employ the handling equipment. Since the density of truck arrivals is high and the number of service request in short period of time is high, maybe it is possible to delay truck service by some short period of time to give the terminal operator information about the truck location in the slots and the exact location of the container in the yard that is associated with that truck. By varying the planning period we can take advantage of opportunities for efficient match at the edge of the planning period. Therefore, the question that arises is whether the optimal length of the planning period is 1, 2, 5 or 10 minutes or more.

4.5 Objectives

The objective of this dissertation is to develop a new approach to optimizing container handling equipment operations that will be beneficial to the terminal operator in terms of improving productivity, providing faster service and reducing operating cost. The proposed solution needs to also provide acceptable service for truckers. The operational strategies that are presented will be able to assess the operation from truckers and terminal operator's perspective.

The main question that the terminal operator faces is "Can I provide adequate quality of service and at the same time minimize my capital and operating cost related to the straddle carrier operation? The questions that this dissertation answers are stated as follows:

1. What is the optimal assignment of straddle carriers to trucks given the time dependent nature of the assignment?
2. What is the optimal length of the planning period?
3. What is the optimal straddle carrier fleet size that needs to be deployed to service the trucks?
4. What is the relationship between the truck arrival rate given a straddle carrier fleet size requirement and the planning period length? How the arrival rate impacts the straddle carrier fleet size and the planning period?
5. What is the relationship between the arrival rate, the cost of operation, the straddle carrier fleet size and the planning period?
6. How are costs changing with the change in straddle carrier fleet size and planning horizon? Are there economies of scale in the operation?

CHAPTER 5

LITERATURE REVIEW

Most studies on the port planning and simulation focus on the water side rather than on the land side – namely they are concerned with improving ship service rather than truck service. The reason for this bias is that a ship's downtime costs and customer demands are higher and more critical than their land counterparts. This does not mean that optimizing truck servicing and equipment utilization is of no importance. Since a terminal's performance is judged on the overall performance of its individual components, this bias is not justified.

The literature review consists of three segments:

- Algorithms and operations research techniques used for different problems of assigning equipment to ships or trucks as a separate system
- Operation of a container terminal as a system, terminal design, evaluation and terminal simulation as a complete system
- Review of the algorithm used to solve the objective of this dissertation

The sections that follows are organized based on the above segments.

5.1 Algorithms for Assigning Equipment at a Container Terminal

The Straddle Scheduling Procedure (SSP) considers the dependency between sequential assignment procedures to solve the problem of assigning straddle carriers when they arrive to the slotted area (Das and Spasovic 1999). This methodology attempts to pair closely located drop-off jobs with pickup jobs. If the straddle carrier is available in the slot area then the first preference is to assign it to a drop-off truck that is already slotted.

The assignment algorithm is used as a base for this procedure, and the whole routing consists of six steps. When a new truck is slotted, the SSP basically checks which straddle carrier is available and assigns the nearest one. If the straddle carrier is available, the SSP compute the assignment cost for each truck, which is weighted objective function, and by using Hungarian method finds the best assignment of straddle carriers to trucks. The Straddle Scheduling Procedure (SSP), based on the experiments, was being compared to the Closest Job Assignment method and Greedy Assignment Procedure and it provided significant savings in empty straddle travel when compared to the other two methods. Also, by reducing the straddle carrier fleet size the waiting time increased by a small margin and it was shown that the value of SSP scheduling increases as material handling resources are more constrained. Also, a significant reduction in net schedule cost was made and truck waiting time was smaller compared to the alternative strategies.

Different methods for scheduling straddle carriers, automated guided vehicles (AGV's), reefer workers and stacking cranes were tested in a container terminal system (Hartman 2004). The straddle carrier operation is demonstrated on three cases where straddle carriers provide service to quay cranes or external trucks by delivering containers from the yard. The assignment of straddle carriers has the objective of minimizing the waiting time of quay cranes and trucks on containers. The first heuristic that was used to dispatch equipment to jobs is a Priority rule based heuristic that follows four steps (compute eligible jobs, select job, select resource and update schedule) to schedule all jobs. This heuristic was used on two methods; the first method is a single pass dispatching method that produces one schedule. The Second method is a multi pass sampling method that produces different schedules by randomizing the minimum due date priority rule.

The application of the Genetic Algorithm, which adopts the principles of biological evolution to solve optimization problems, was also used to solve the assignment problem. The genetic Algorithm often does not operate on schedules but on representation of schedules. The results showed that the genetic algorithm produces better results than the priority rule methods. The initial population and the sampling process, had an impact on the results obtained by implementing Genetic Algorithm scheduling method.

The real time optimization assignment of AGV's to service quay cranes and trucks was the focus of research done by Briskon et al. (2004). To assign AGV's, a Greedy Priority rule heuristic optimized the time at which an AGV should arrive at a quay crane. The main goal is to maximize productivity of quay cranes (i.e., if more containers are handled by quay cranes then there will be a shorter turnaround time of ships). To achieve higher productivity, the waiting time of quay cranes on AGV's has to be minimized. To reach that goal, for example, the minimization of empty travel time of AGV's or a better distribution of AGV's to quay cranes can be an objective. The heuristic tries to prevent the AGV of arriving early or being late at the quay crane, which means that an AGV has to reach the quay crane just in time when it becomes available. If an AGV arrives early, it will wait for the quay crane to become available and that is a waste of AGVs time. If the AGV comes late, the quay crane is waiting for an AGV. The assignment is solved by using the Hungarian algorithm with the objective function of minimizing the due time that is calculated as a time between the arrival time of AGV to the quay crane and the time when the quay crane is ready to service that particular AGV. The second solution is obtained by using the Greedy Heuristic with a Priority Rule. The first step is to select a job with the smallest due time. This is accomplished by selecting the AGV that leads to the smallest possible increase in the objective function. An Inventory-based approach treats a quay crane as a customer. Each quay crane has a buffer which contains AGV's that are assigned to that quay crane. Every time when AGV gets a job it is assigned to the quay crane that has the smallest buffer. To compare the results of the Hungarian and the Greedy Heuristic assignment with the Inventory rule, assignment simulation is used. The Hungarian algorithm compared to the Greedy heuristic only increased productivity by 1.0-1.8%. The smallest empty travel times of AGV's are obtained by using the inventory based approach.

The assignment of straddle carriers at a container terminal was evaluated by Steenken (1993) with the goal to minimize distance the straddles traverse without carrying a load. Different heuristics were applied to solve this problem. The Balance and Connect approach starts with solving the assignment problem. The initial step is to balance the network and then connect the network by solving a minimum spanning tree problem. The Balance and Connect model is expanded to the Multiple Rural Postman problem (MRPP). Another model used to match straddle carriers to jobs is based on a Machine scheduling (MAS) and contains three dispatching rules:

- Shortest processing time (SPT). The jobs with shortest processing time have a priority to be assigned first
- Longest processing time (LPT). Jobs are assigned based on decreasing processing time
- Earliest due date (EDD). Jobs are ranked based on increasing due date.

The MAS model was compared to the MRPP and the results showed that the MAS outperformed the MRPP. When the observed operational time period was extended to one week of data the MRPP had better results by reducing the empty load trips by 28% compared to 26% achieved by MAS.

An approach of routing straddle carriers that deliver containers to yard trucks that are assigned to quay crane was developed by Kim et al. (1999) with the objective of minimizing the total travel distance of the straddle carriers between yard bays. The operation of loading containers to the ship consists of two segments. Straddle carriers in the yard are locating containers and loading them on to a yard truck. Usually three to four yard trucks are delivering containers to quay cranes and they are assigned only to one straddle carrier. Since containers are differentiated by type and group, constraints that have to be met are that the loading sequence must satisfy the loading schedule of quay cranes and that the total number of containers of each group handled by straddle carrier must be equal to the corresponding group stored at the yard. The assumption is that one straddle carrier is assigned to one quay crane, and to solve this assignment a two-stage algorithm is proposed. At the beginning containers in the yard are first assigned to quay crane and then carrier routing is performed for the set of selected containers. The problem is decomposed to set of independent problems which are then solved as a transportation problem. When set of containers for a specific quay crane is determined, the routing of the straddle carriers is performed by using a beam search algorithm. For a set of containers, the tour of straddle carrier is defined. The results show that the travel distance of the straddle carrier can be reduced if the number of blocks that he is visiting is minimal and that can be achieved by assigning individual container groups to smaller number of blocks.

The movement of containers by gantry cranes and straddle carriers between the ship and the container yard was studied by Böse et al. (2000). The scope of the study was to simplify the operation of the container terminal in Hamburg, Germany. The current operational strategy is that a fixed number of straddle carriers are servicing a single quay crane. Thus, an efficient gantry crane operation can be achieved by efficiently scheduling straddle carriers. The gantry cranes are unloading containers from the ships and placing them in the buffer bellow the cranes. Thus, the container is available to be scheduled for straddle carrier assignment. When a container is placed in the buffer, the event is called the birth time. When a straddle carrier delivers a container to be transferred to the ship by a gantry crane and leaves it in the buffer, this event is also called a birth time. The objective is to minimize a delay that is defined as time period between the birth time and the moment when the straddle carrier arrives to pick-up the container from the buffer. The model is simplified by not considering the stacking of containers in the buffer zone. The paper explores two possible assignment strategies of straddles to quay cranes. The first one is a semi-static assignment where a fixed number of straddle carriers is assigned to a particular quay crane. The second one is a dynamic assignment where a fixed number of straddle carriers can be assigned to any of the cranes that are in service. The straddle carrier fleet size in operation is set to be three times the number of gantry cranes. The application of the genetic algorithm is compared to the implementation of the semi-static and dynamic assignments. The results presented the advantage of the genetic algorithm on reducing delays in quay crane operation. The total distance travelled by straddle carriers and the empty tours are also reduced, while the time that is needed to process the container vessel is also reduced.

Optimal container storage strategy is in correlation with developing an optimal schedule for container handling equipment. Kozan and Preston (2006) modeled a container allocation problem that minimizes the handling time for all containers coming off ships and at the same time minimizes the container transfer time to the storage area. When a ship arrives at the port, the Container Transfer Model (CTM) allocates the necessary equipment needed to service the ship. The CTM tries to minimize the transfer times of containers from the ship to the storage area and vice versa. The Container Location Model (CLM) is designed to minimize the handling time of containers in the storage area. The CTM and CLM are integrated when these two systems are close. The models aim to simultaneously optimize the container transfer and storage handling time. The model solves the two problems independently and results from one model are used as input data for the second model. At first, the CTM determines the container transfer using a random initial storage location. Then, the output, the handling schedule is used as input for the CLM. The result from CLM is the optimal location of the containers at the yard, and this information is used again as an input for CTM. This process is performed until a stopping criterion is satisfied. Solution techniques used are the genetic algorithm, a tabu search algorithm and a hybrid of genetic and tabu search algorithms. The genetic algorithm gave better results than the other two algorithms. It was observed that by reducing the maximum storage height of containers resulted in a reduction in the turnaround time.

Murty et al. (2003) classified the daily operations of a container terminal into nine decisions ; namely, allocation of berths to arriving ships, allocation of quay cranes to docked ships, appointment times to external trucks, routing of trucks, dispatch policy at the terminal gate and the dock, storage space assignment, RTGC deployment, IT allocation to QC, and IT hiring plans. The measures of performance that are usually optimized are:

- The average waiting time of external trucks that are delivering outbound containers or picking-up inbound containers
- The average waiting time of internal transport vehicles that are waiting for quay cranes or yard equipment to load/unload a container to/from them
- The waiting time of quay cranes waiting for internal transport vehicles
- The total number of internal transport vehicles that are being used during the shift
- The number of unproductive moves that are being made in the storage area

The Optimal deployment of Rubber Tired Gantry Cranes (RTGC) in the storage yard was developed for a 4-hour deployment period. Since the workload in the block where containers are stacked changes over time, it was specified that maximum of two RTGCs can work simultaneously within one block area. The model is based on the layout of the Hong Kong container terminal which consists of 70 storage blocks and has 98 RTGCs in service during the day. The mathematic model was based on the transportation problem formulation and the objective was to minimize the empty travel time that occurs when RTGCs move between jobs. For the numerical example the deployment of RTGCs to storage blocks was solved as a transportation problem and the objective was to optimally deploy RTGCs to blocks.

The implementation of various dispatching strategies in automated container terminals has the goal of using the least number of equipment needed to serve the quay cranes. Vis and Bakker (2005) explored different dispatching strategies to determine the optimal number of automated guided vehicles (AGV's) needed to service the quay cranes. The operation modeled begins with unloading a container by quay cranes at initial moment followed with dispatching of AGV's. Dispatching of AGV's is tested with four different strategies. The first dispatching rule assigns the nearest automated guided vehicle to a container that is being unloaded. The second dispatching rule starts with the assignment of the farthest AGV to container. A random assignment is used as a third method, where the algorithm assigns randomly available AGV to containers. The last dispatching rule is a Cyclic rule that selects the first available AGV beginning with the successor of the last AGV selected so that a balance in workload among all AGVs is achieved. The model considered only differences in container size (20 foot and 40 foot) but did not differentiate the position of the container in the stack. The number of AGV's in operation was from 24 to 36 and four cranes were used to unload 2500 containers. To compare the performance of dispatching rules used to assign AGVs to cranes three parameters were used; total cycle time defined as the total time required to unload all containers off the ship, minimum number of AGV's required to achieve a minimal total cycle time, and average utilization of AGV's. The results obtained using the nearest vehicle rule demonstrated that the smallest cycle time is obtained and less number of AGVs is needed to be in operation to reduce the total cycle time.

Kim and Kim (2002) discussed methods for routing yard equipment during loading operations in a container terminal. The yard equipment consists of yard cranes and straddle carriers that are transferring containers onto yard trucks based on a predetermined assignment. Minimizing the total container handling time is the objective of the paper. This paper considered the case when only one quay crane is in operation and a single yard equipment is in operation. To solve this problem different algorithms were used. An algorithm based on dynamic programming enumerated all possible solutions to find the least cost route based on the set of constraints. The genetic algorithm was a second algorithm used to minimize the total container handling time. The third algorithm was a neighborhood beam search algorithm that initially developed a basic feasible solution and then by branching for every pair of two containers the locations were exchanged. After all nodes are explored the best promising solutions are chosen and branching continues from those nodes until all nodes are covered and the best solution obtained. To compare the results, two set of problems were used to test the algorithms. First, ten small size problems with 48 containers randomly distributed in the yard were generated. The large sized problems consisted of 30 yard bays with 243 containers randomly distributed. The optimal solution generated by using dynamic programming was compared with solutions obtained from the genetic and neighborhood search algorithms. The neighborhood beam search algorithm had slightly better results than the genetic algorithm when travel distances are compared. Also for large size problems the neighborhood beam search algorithm outperformed the genetic algorithm.

Meersmans and Wagelmans (2001) used a Branch and Bound algorithm for the problem of scheduling handling equipment in container terminals with the objective of minimizing the makespan of the schedule. The container handling operation in the terminal is based on a combination of Automated Guided vehicles (AGVs) delivering containers to quay cranes and then the quay cranes are loading those containers to the ship. The yard equipment, automated stacker cranes (ASC), are transferring containers from the yard to AGVs. First the lower level bounds are found and they are used to discard the nodes that are not giving better solutions. Whenever the number of nodes that are being evaluated excides 10^5, the algorithm stops and the current best solution is used as an optimal solution. The second heuristic used is a beam search algorithm that is related to the branch and bound algorithm. The number of container moves that are being considered varies between 8 and 168 and they are being handled by a maximum of 27 automated stacking cranes and 24 AGVs. The number of cranes in operation varies between 2 and 4. The results from both algorithms are compared for different problem sizes and the results by both algorithms are similar. The computational time for the Branch and Bound algorithm is 10 to 20 times longer than time of the Beam Search algorithm.

Froyland et al. (2006) developed a model that incorporates more variables into simulating the operation of a container terminal so that the simulation can represent better real world operations. The data used is a historical 30 day operation data obtained from Port Botany located south-east of Sydney. Rail mounted gantry cranes (RMG) are handling containers and moving them to an intermediate storage area for quick transfer to trucks or trains. The container handling within the terminal is performed with straddle carriers. The objective is to find a schedule and route for RMGs that optimizes their utilization, while minimizing the straddle carrier fleet size. The excess equipment can be utilized in other sections of the terminal for container handling. The terminal area is divided into three sections: the Gantry-road Interface consist of 60 truck slots and two railway tracks for transfer of container to or from trains and trucks. This part of the terminal was not part of the optimization. The Gantry-Straddle interface is the yard are used to store export containers that are delivered up to 12 hours before ship arrival time. This interface is part of the optimization process and the optimization is performed by pairing moves. The intermediate Stacking Area is located between two other interfaces and it is used for storage of import containers arrived by trucks or trains and these containers are then moved from this are to ships and other trains. The operation within this terminal is performed by semi-automated rail mounted gantry cranes. To simplify the model the size of containers and type (reefer, containers with dangerous goods etc.) of containers are not taken into consideration. The optimization was divided into three problems. At the initial step a strategic integer program estimates the movement time of containers between the intermediate stacking area and gantry straddle interface by determining the schedule. Each container has to be moved within the specified time window and an integer program minimizes the number of straddle carriers needed to be in operation during each hour. Also, the utilization of the intermediate stacking area (ISA) has to be within its limits. The results are the utilization of ISA, the number of operations of the rail mounted gantry cranes, dwell time of containers at the ISA. It was determined that seven straddle carriers are needed for optimal operation. At the second step, the integer programs are used to solve the position of containers at the gantry-straddle interface (GSI) and at the third step a model based on the online algorithm assigns rail mounted gantry cranes from the Gantry Rail Interface to containers from gantry-straddle interface. The results showing the utilization of the rail mounted gantry cranes and it was indicated that the around 15% of the total moves are empty moves and 67.5% involve loading and unloading operations. Also, 3% of the trucks experienced an excessive waiting time, since the arrival rate of trucks was high and cranes could not handle them in time.

Rashidi and Tsang (1999) wrote a systematic review of problems associated with a container terminal. The document describes five different scheduling problems and decisions that have to be made. The first problem analyzed is the berth allocation to ships and quay cranes allocation to docked ships with the goal of minimizing ship waiting times and maximizing the port's turnaround. The second decision is to determine the storage space in the storage area for containers so that reorganizing and reshuffling of containers is minimized, which leads to minimizing the cost per container. The third problem deals with Rubber Tyred Gantry Crane (RTGC) assignment in the yard that affects quay crane performance and the performance of vehicles that transport containers as well. The fourth decision that has to be made is scheduling vehicles that transport containers between the yard and quay, and the objective is to minimize the transportation cost and waiting time of quay cranes and RTGCs. The final problem presented is the processing of external trucks arriving to pick up or deliver containers. The goal is to minimize the waiting time of trucks and congestion at the gate. For each of these problems the objective function and constraints that have to be met are presented.

Tsang (1994) wrote a review of scheduling techniques that can help a problem solver to better understand which scheduling methodology should be used based on the objective of the problem. Basic questions are proposed, whose answers can help the problem solver to choose the appropriate scheduling algorithm. Some of the scheduling techniques such as linear programming, branch and bound, tabu search, genetic algorithm etc. are explained and the type of scheduling problems they can be used are listed in Table 5.1.

Table 5.1 Considerations in Choosing Among Major Scheduling Techniques

	General Considerations	Major technique specific considerations
Linear Programming	Used for optimization with linear functions Intractable	Problem must be specified by a (normally conjunctive) set of inequalities
Branch & Bound	Used for optimization Intractable	Require heuristic for pruning Ordering of branches is important
Tabu Search		Effectiveness mainly depends on strategy on tabu-list manipulation
Genetic Algorithms	Useful for finding near-optimal solutions Requires nontrivial time, but hopefully will search a wider part of the solution space	Representation is crucial Effectiveness could be sensitive to choice of parameter values and operators

5.2 Container Terminal Operation, Design and Simulation

A classification and literature review for container terminal operations have been provided by Steenken et al. (2004). The authors divided the review into ship planning processes, stowage and stacking logistics, and transportation problems. In their classification, the first category consists of berth allocation, the stowage planning process and crane allocation. The decisions related to yard cranes and storage area allocation are in the second category. The third category of the decisions refers to transportation problems from the quay side to the storage area or vice versa, the container handling equipment movement from their source to their destination and to traffic inside the terminal. From the logistics point of view, a gain in ship productivity cannot be necessarily achieved by increasing the number of equipment that are servicing the cranes, since that might create congestion, thus the optimization system has to be developed that deals with minimizing congestion. Processing of trucks is described as a dynamic system that changes in time due to permanently changing traffic volume. The optimization has to be flexible and fast, and online optimization is a possible technique that leads to good results. In this problem, minimizing empty distances and the travel times are the main focus of optimization and this can be achieved by combining transport of export containers from the yard to trucks with import containers that are taken off from the trucks and stored at the yard.

Sgouridis and Angelides (2002) developed a simulation model that simulates the handling of inbound containers by straddle carriers. The model has the characteristics of Thessaloniki's container terminal where yard equipment that handles containers consists of straddle carriers only. The containers are unloaded from the ship by quay cranes and stacked in the import area by straddle carriers that are only assigned to cranes. The trucks are unloaded by straddle carriers assigned to the import area, and those containers are transported to the export area by the same straddle carriers. The simulation model gives insights on how import area functions by calculating equipment utilization and truck turnaround time. The model estimates the required number of straddle carriers to ensure an acceptable level of service and it demonstrates the benefits of implementing an automated container management system. The software used in developing the models is called "Extend" and it simulates discrete event problems. As input variable characteristics of the stacking yard, shift pattern, yard filling rate, arrival distribution for trucks depending on load status, straddle carrier operational parameters, duration for system operations and information regarding general port organization methods are used. The output of the simulations is generated as a report that contains average queue time, total time, cycle time, average service and wait time, utilization of the straddle carriers, number of trucks processed per shift, etc. The truck arrival times are assumed to follow Erlang distribution with m=2 and k=2.The Erlang distribution is also used for the inter arrival times in the server-client system. A validation of the simulation model was performed based on real world information. The historical data for truck arrival times for each day was used an input. A straddle carrier utilization of 70% was recommended by manufacturers for the cost effective utilization of equipment.

Behera et. al. (2002) discussed the terminal yard operations and developed a simulation model to examine the impact of the straddle carrier fleet size on the terminal overall throughput. The researchers compared two different job assignment rules. A service based on the first-in-first-served principle was tested against a simple heuristic that assigns each job to the closest available straddle carrier. The simulation results revealed that both the old and new rules performed equally well using performance indicators such as average container flow time, daily throughput, average waiting time of jobs, number of jobs in the queue, and straddle utilization.

5.3 Assignment Algorithm

The problem of assigning equipment, personnel etc. asks for the best assignment of a set of machines and people to a set of jobs. Kuhn (1955) developed a methodology to answer the question of assigning *n* individuals to *n* jobs that maximizes the benefit and no job is assigned to two different individuals.

The general assignment problem consists of the choice of one job, from the set of *n* available jobs (j=1, 2,. . . , n), and for each individual from the set of individuals n (i=1,2, . . . ,n), such that only one job is assigned to one individual. Given an n by n matrix R=(r_{ij}) of positive integers, find the permutation j_1, . . . , j_n of integers 1, 2, . . . , n, the assignment maximizes the sum $r_{1j_1} + \ldots + r_{nj_n}$. A liner dual program is then used to transform this problem to a minimization problem that is finding non-negative integers u_1, . . . , u_n and v_1, . . . , v_n subject to

$$u_i + v_j \geq r_{ij} \quad (i, j = 1, 2, \ldots, n) \tag{1}$$

that will minimize the sum $u_1 + \ldots + u_n + v_1 + \ldots + v_n$

To solve the minimization problem, the algorithm is using two basic routines called Routine I and Routine II and on Figure 5.1 the order of their repetitions is given.

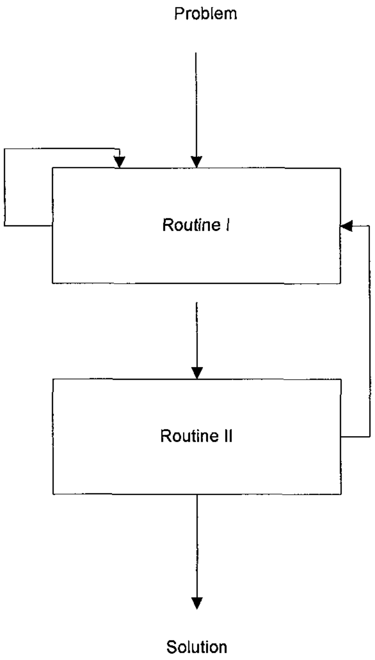


Figure 5.1 Schematic description of the order of repetition of routines

A set of non-negative integers that satisfies the constraint (1) is called a cover and the position (i, j) in the matrix for which equality holds is said to be marked; otherwise it is said to be blank. A set of marks is called independent if there are no two marks that lie in the same line. Routine I is associated with a fixed cover $\{u_i, v_j\}$. The basis for Kuhn's Algorithm is outlined in the following form:

Step A. Subtract the smallest element in matrix R from each element of R, obtaining a matrix R_1, with non negative elements and at least one zero.

Step B. Find a minimal set of lines S_1, n_1 in number, which contains all the zeros of R_1. If n1 = n there is a set of n independent zeros and the elements of R in these n positions constitute the required solution.

Step C. If $n_1<n$, let h_1 denote the smallest element of R_1 which is not in any line of S_1. Then $h_1>0$. For each line in S_1, add h_1 to every element of that line; then subtract h_1 from every element of R_1. Call the new matrix R_2.

Step D. Repeat steps B and C using R_2 in place of R_1. The sum of the elements of the matrix is decreased by $n(n-n_k)h_k$ in each application of Step C, so the process must terminate after a finite number of steps.

Munkres (1975) developed a variation of Kuhn's algorithm for the assignment and transportation problems. The algorithm is used for the allocation of ships so that one location has a specific number of ships and at the the cost of moving ships between locations is minimized. The problem statement is: There are N ships placed at positions $P_1, \ldots, P_n$, and r_i denotes the number of ships at position Pi. If somebody wants to move ships to a new position Q1, . . . , Q_m so that there will be c_j ships at position Q_j. the number dij is the cost of moving a ship from position P_i to position Q_j. The number x_{ij} stands for the number of ships that will be moved to a different position and it will be called the quota assigned to d_{ij}. The problem is to choose these quotas so that the total cost of moving the ships is as small as possible. Such a choice of quotas is called an optimal solution of the assignment problem The solution is obtained by using Steps A, B, C and D from above.

Kumar (2006) proposed a modified method for solving the unbalanced assignment problem where the number of jobs, *m*, is larger than the number of available workers, *n*. For the initial matrix that is generated, the sum of rows and columns is calculated and sorted in ascending order. Two matrices are then created. The first matrix is a square *(nxn)* matrix that can be solved by the Hungarian method and the result is an optimal assignment. Starting from the first smallest value of row sums, corresponding row from the original matrix is a new row in first matrix. This approach is repeated until *n* new rows are generated. The second matrix represents the assignment of the workers to remaining jobs and can be interpreted as the assignment of fictitious workers to machines. The minimal value in the sums of columns is selected and corresponding column is selected to generate the first column of the second matrix. The process is repeated until m-n columns are selected.

In real life situations it is difficult to balance jobs and machines. Not always we have the case that the number of available persons is same as the number of jobs that has to be completed. In the case of unbalanced assignment problem the literature suggest adding fictitious jobs or workers to obtain the balanced assignment problem. Solving this problem results in an assignment of some jobs to fictitious machines or persons. This fictitious assignment can be ignored in the final result.

5.4 Summary

The literature review provided the knowledge of how the complex systems in the port operates and what should be the right way to analyze the operation of straddle carriers. Studies by Das and Spasovic and Steenken provided the groundwork for the investigation of processes, methodologies and objectives associated with equipment assignment in the port, and they will be used as the basis for the algorithms that will be used in this dissertation. Although there are a significant number of studies done on the topic of assigning equipment in container terminals, the literature review did not present any attempts of postponing decisions regarding dispatching equipment with the goal of improving service that this research explores. The literature review provided knowledge regarding the objectives of terminal management and what are the important decision variables in evaluating operations. The review of different assignment algorithms and heuristics concluded that there is no single best algorithm that gives the best results.

CHAPTER 6

ASSIGNMENT MODELS FOR STRADDLE CARRIER SCHEDULING PROBLEM

Many of the problems that management faces in designing logistics operations can be associated to some general classes of transportation and network routing problems. Operations optimization using methods of operations research in container terminals has become imperative, since the operations are very complex and further improvements can be made using scientific methods.

This chapter defines the assignment models that will be used to a case study in attempt to answer the research question stated in Section 4.3. The assignment logic and scheduling methodology will describe the continuous time dependable assignment process of straddle carriers to trucks.

6.1 Objective Function in Assignment Problems

The literature review identified different objectives in solving the problem of assigning and scheduling equipment in a container terminal. The objective of the straddle carrier assignment problem can be either minimizing truck waiting time, minimizing the total straddle carrier travel distance, or minimizing the total distance that straddles traverse without carrying loads. Also, it is possible to have a combination of different objectives. The objectives are given priority based on a weight. A sample objective function is shown bellow.

Objective Function = α * straddle distance travelled + β *delay in servicing trucks

Where:

α is a travel cost per unit distance for straddle carrier

β is a linear cost penalty for delay in servicing a truck

The objective function used in this dissertation is to minimize the total distance traveled by straddle carriers, defined as the sum of distances that straddle carriers need to travel to (from) trucks and pick-up (deliver) containers and the distance that carriers need to traverse in order to drop (pick-up) containers to (from) the yard.

6.2 The Straddle Carrier Assignment Models

The following algorithms and heuristics are used:

- Heuristic based on the First Come First Served (FCFS) Rule: The straddle carrier is assigned to the first truck entering a slot in the yard
- Heuristics based on the Hungarian Algorithm
- Heuristic based on Implicit Enumeration

6.2.1 Heuristic I. Application of the First Come First Served (FCFS) Rule

As soon as the first truck enters a slot, the straddle carrier that is closest to it is assigned to service it. This is the first come first served rule (FCFS). The algorithm assignment procedure is presented in Figure 6.1.

As the truck enters the slot, the algorithm examines which straddle carrier, from the pool of available carriers, is closest to the truck. If all straddle carriers are busy as the truck enters the slot, the algorithm calculates which straddle carrier is going to be available first, and then it assigns that straddle carrier to the truck in the slot. The algorithm follows this logic until all trucks are processed.

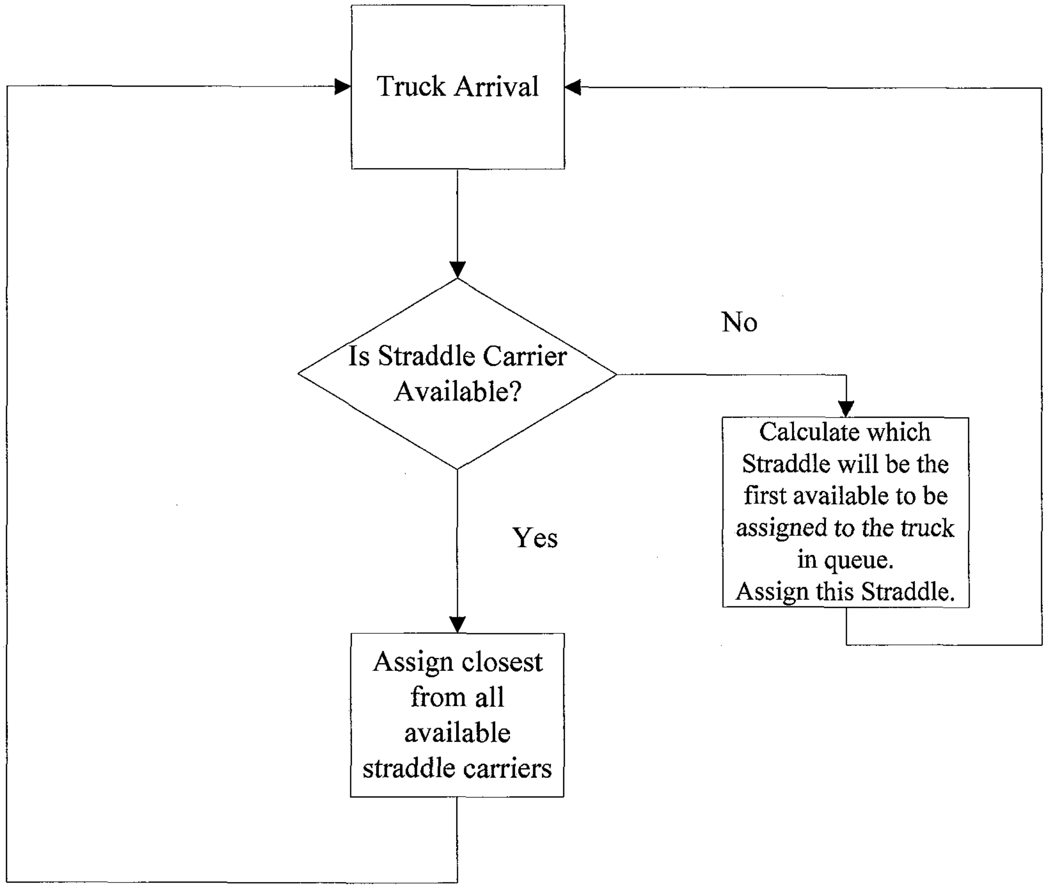


Figure 6.1 Assignment logic based on FCFS rule

6.2.2 Hungarian Algorithm for Straddle Carrier Assignment

The development of this algorithm was motivated by an idea that if one can partition the continuous arrival of trucks during a day into a sequence of time frames of certain duration, and if the optimal static assignment can be made within each time frame, then the resulting approach with yield an optimal assignment for the entire operating day. To this end, we need to find the optimal time offset from the moment a truck is slotted and until it is assigned to a straddle. To elaborate on the algorithm, the following terminology and operating rules need to be introduced.

Terminology and Operating Rules

- T_o denotes the fixed point in time at which the algorithm calculates the assignment of straddle carriers to trucks
- The planning period is defined as a time interval from the moment when the first truck enters the slot until time T_o when the first straddle carrier is dispatched (e.g. T_o, $2T_o$).
- During the planning period, the straddle carriers are not assigned to arriving trucks.
- The job execution period is the time interval (T_o, T_{oE}) during which the straddle carriers are servicing trucks.

The question arises as to how to treat the acceptable limit of truck wait time. Two different approaches are used for this. They are discussed in turn.

6.2.2.1 Hungarian Algorithm I - No Limits on Truck Wait Time

The events of the operation for which the algorithm is developed are shown on Figure 6.2. Trucks are arriving at the slots during a certain period. This period is called the planning period and is designated by the [0, T_o] time interval. The trucks are added to a truck queue. At the end of the planning period at time T_o, an assignment of straddles to trucks is made. The straddle carriers are assigned to trucks by using the Hungarian Assignment. The resulting straddle jobs are executed during the job execution stage designated as the [T_o, T_{oE}] period. If a straddle carrier finishes its assignment before the time period ends ($2T_o$), it waits until the next dispatching schedule is made at time ($2T_o$).

The length of the planning period will be varied and the optimal solution identified. The solution with the least total travel distance will be declared as the optimal and the resulting optimal straddle carrier fleet size and the planning period duration noted.

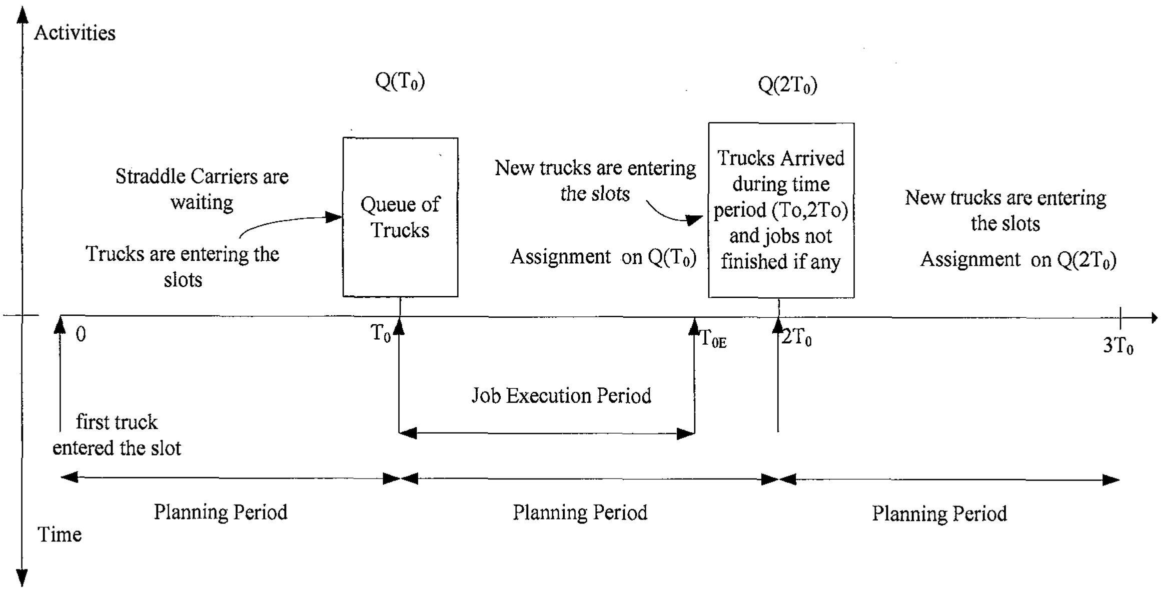


Figure 6.2 Planning period and assignment process

Assignment Logic

The decision process is described as follows:

Step 1. Determine which straddle carriers are available to be assigned to trucks waiting in the queue. For the initial assignment at T_o, all straddle carriers are available and the algorithm proceeds to Step 2. If the straddle carriers are not available, wait until the planning period expires and go to Step 4.

Step 2. Calculate an optimal assignment of straddle carriers to trucks that minimizes the total distance travelled by each straddle carrier-truck pair. Use the Hungarian Algorithm to obtain the optimal solution. Calculate the job execution time, namely the time when the straddle carriers will become available for the next assignment.

Step 3. Carry out the assignment - dispatch the straddles to the trucks. Add any unassigned trucks to the unassigned truck queue. Wait until the end of the job execution period.

Step 4. After the job execution period has expired, examine the truck queue (The queue consists of unassigned truck from the previous planning period and newly arrived trucks (those arrived during the job execution period). Proceed to Step 1.

The above assignment Logic is presented on Figure 6.3

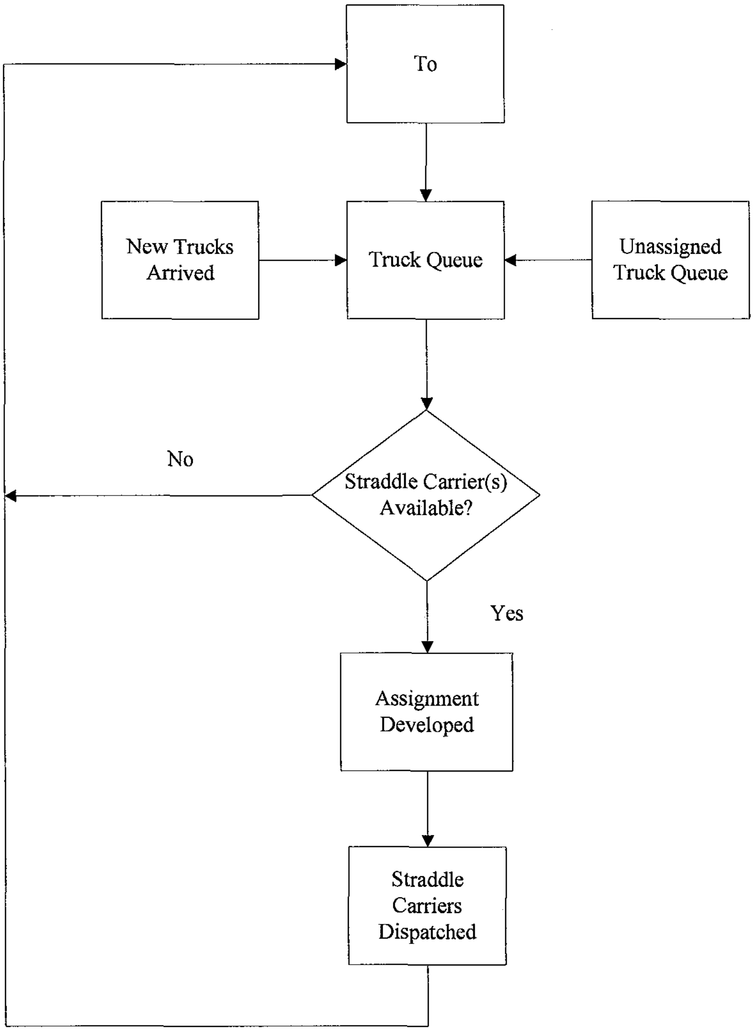


Figure 6.3 Logic for Hungarian assignment without the limit on truck wait time

6.2.2.2 Hungarian Algorithm II – Truck Priority Rule

This algorithm addresses the issue of excessively large waiting times that can occur as a result of the previous algorithm. It accomplishes this by giving priority to the trucks that can be processed during the same planning period. This means that a straddle carrier will be assigned to those trucks that can be processed in the shortest possible time before the planning period ends. If the time required to process a truck is longer than the remained of the planning period, then the truck will not be processed.

If a straddle carrier finishes its assignment before the time period ends ($2T_o$), it will evaluate if it can make another assignment until the next dispatching schedule is made at time ($2T_o$). If the assignment is possible, a straddle (or set of straddles) that has accomplished its job early is assigned to the trucks in the queue.

The events of the operation shown on Figure 6.2 are also used here. However, in marked contrast to Figure 6.2, the events in Figure 6.4 allow for the straddles to be reassigned to trucks for jobs that can be performed before the start of the next planning horizon. Namely, the assignment is carried out if it can be completed during the [T_{oE}, $2T_o$] period.

This change in the assignment is shown in the algorithm steps listed in Figure 6.5.

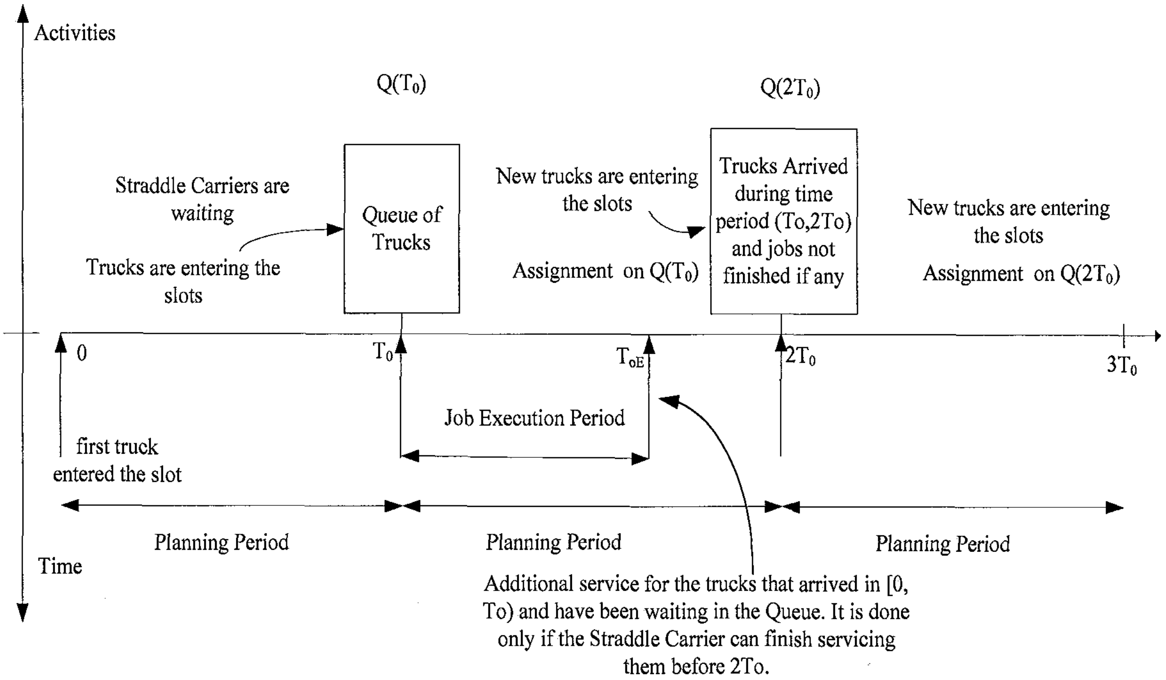


Figure 6.4 Modified assignment process

Algorithm Logic

The algorithm is as follows:

Step 1. The algorithm determines if straddle carriers are available to be assigned to trucks waiting in the queue. For the initial assignment at T_o, all straddle carriers are available. If the straddle carriers are not available, proceed to Step 5.

Step 2. Calculate an optimal assignment of straddle carriers to trucks that minimizes the total distance travelled by each straddle carrier-truck pair. Use the Hungarian Algorithm to obtain the optimal solution. Calculate the job execution time to determine the time when the straddle carriers will become available for the next assignment.

Step 3. Can the assignment be accomplished before the end of the planning period? If yes, carry out the assignment – dispatch the straddles to the trucks. Go to Step 4. Otherwise, go to Step 5.

Step 4. Are there any trucks from the previous planning period still waiting in the queue? If yes, go to Step 2.

Step 5. Wait until the planning period has ended. Examine the truck queue. The queue consists of unassigned trucks from the previous planning period(s) and the newly arrived trucks during the last period. Proceed to Step 1.

This assignment logic is shown in Figure 6.5 on the next page.

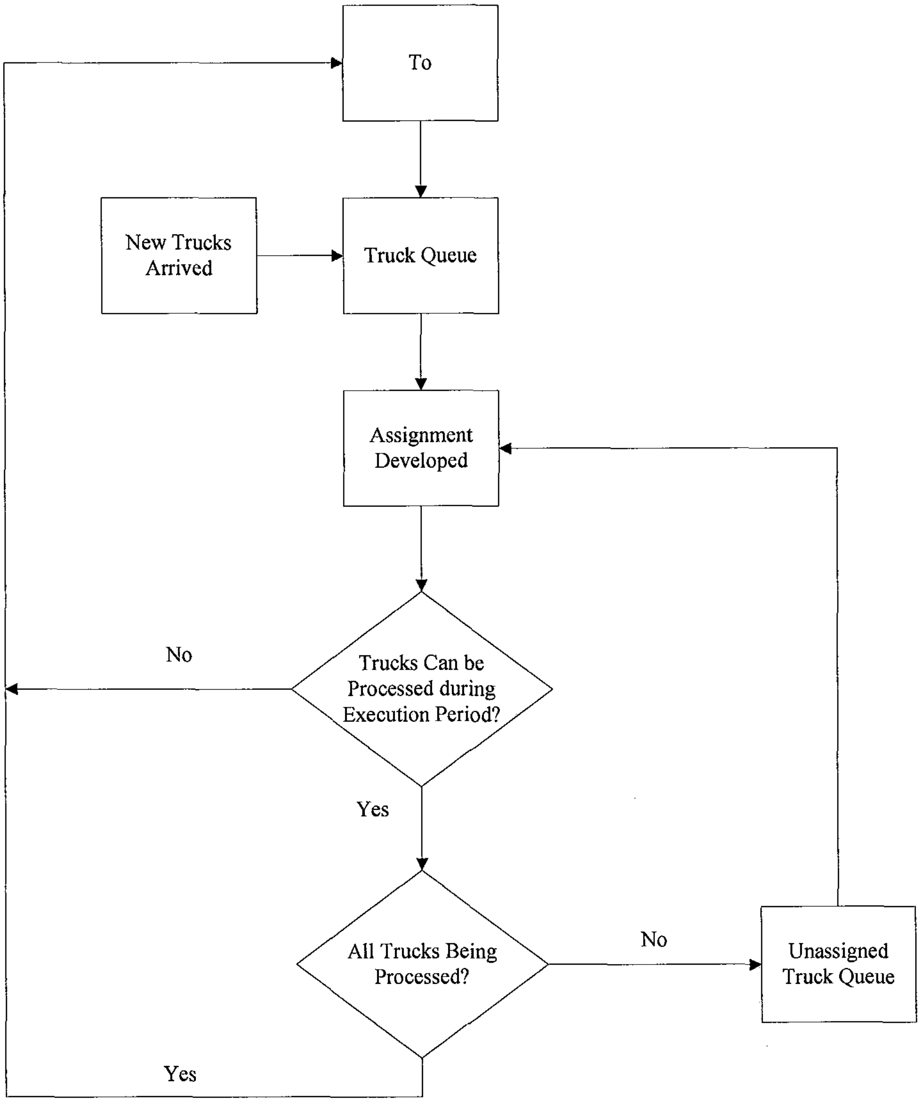


Figure 6.5 Logic for the Hungarian algorithm with priority assignment

6.2.3 Heuristic with Implicit Enumeration

The heuristic presented in this section uses a different approach in assigning straddle carriers than the previous heuristics. It determines a sequence of jobs that each straddle carrier in the fleet has to perform with the objective of minimizing the total distance travelled. It then develops a schedule which assigns a straddle carrier to a truck sequence.

Assignment Procedure

Terminology and Operating Rules

- T_0 denotes the fixed point in time at which the straddle carriers are dispatched to trucks.
- The planning period is defined as the time interval that last from the moment when first truck enters the slot until the time T_0 when the first straddle carrier is dispatched.
- During the planning period straddle carriers are not assigned to trucks that are arriving.
- The job execution is the time interval (T_0, $2T_0$) during which straddle carriers are dispatched and assigned to trucks based on the assignment determined during the planning period.
- The maximum allowed waiting time, w_t, denotes the time that is allowed for a truck to wait until it has to be assigned. The truck that has reached the maximum wait time will be assigned in the next planning period.
- The control time C_t denotes a point in time when the algorithm checks if any truck that is not assigned and it is in the unassigned truck queue has been waiting for more than the maximum allowed waiting time.

The straddle carriers are waiting for the entire duration of the initial planning period (0_0, T_0) before they are assigned to trucks. At time T_0, the assignment of straddle carriers to trucks is made. The straddle carriers are then dispatched to trucks.

The assignment process is shown in Figure 6.6. The straddle carriers carry out the assignment for the duration of the job execution period. If a straddle carrier finishes its last assignment before the planning period ends ($2T_0$), it will wait until the next dispatching schedule is made at time ($2T_0$). If the straddle carrier is busy when the next dispatching schedule has to be determined, it will wait until the next dispatching moment. Only those straddle carriers that are available will be dispatched to trucks in the queue.

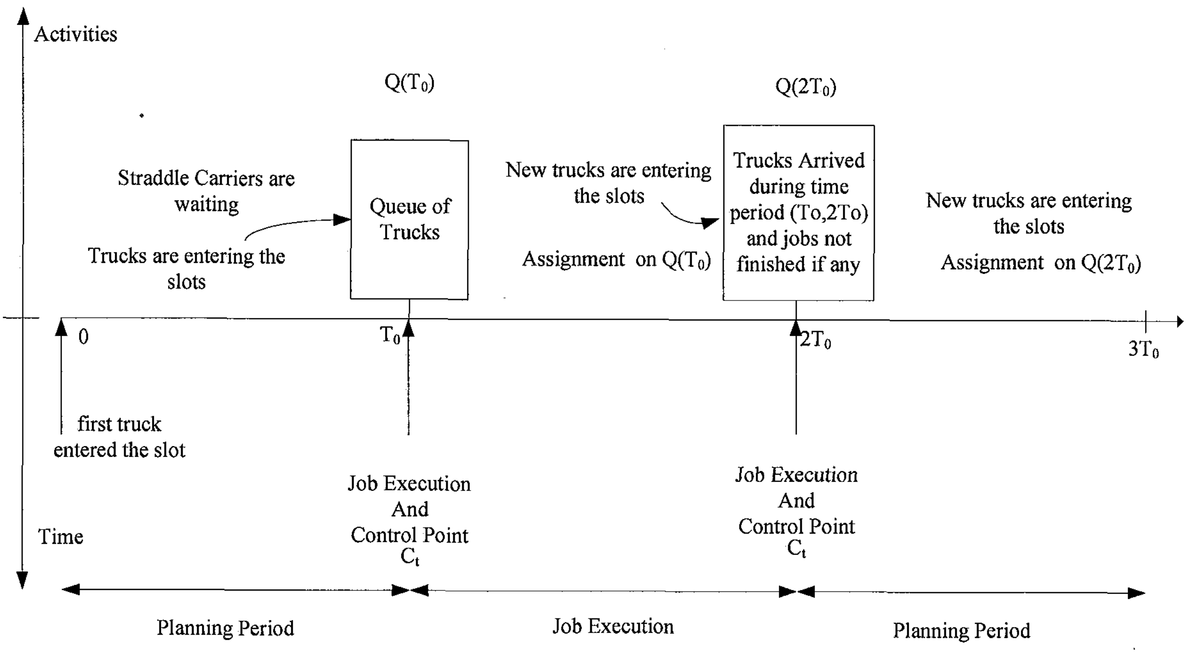


Figure 6.6 Assignment process

At a predetermined time (C_t), before the job execution commences, the algorithm will check if any truck in the queue has been waiting for more them the maximum waiting time w_t, and if it has, this truck will be given priority in the next straddle carrier dispatching cycle.

For this assignment the maximum waiting time w_t was set to 10 minutes. The algorithm, after the optimal schedule has been determined, reexamines the schedule based on how long the trucks are waiting for service. If the truck has been waiting more than 10 minutes, it is moved to the beginning of the queue and prioritized. If more than one truck is determined to be waiting more than 10 minutes, they are moved to the beginning of the queue and are serviced based on who has waited longer.

Heuristic Logic

The process of developing a schedule of assigning trucks to straddle carriers consists of the following steps:

Step 1. Develop an optimal schedule for one straddle carrier that can process all trucks in the fastest manner. For each available straddle carrier determine the truck sequence which minimize the total travelled distance. The truck sequence is determined by using the shortest path algorithm. The shortest distance that single straddle carrier has to traverse to process all trucks is noted as the initial solution and the sequence as the initial schedule.

Step 2. Introduce a second straddle carrier in the operation. From the set of remaining straddle carriers, arbitrarily select a second straddle carrier to be introduced in operation. The algorithm is taking one truck from the initial solution and assigning it to the new straddle carrier. The total distance travelled by both straddle carriers is calculated and compared to the initial solution obtained in Step 1. If the new total distance travelled is smaller than the initial solution, the truck is then permanently assigned to the second straddle carrier. The new total distance travelled is the new solution. If the second straddle carrier was able to improve the solution by taking one truck, it now tries to process another truck so that the total distance traveled is further reduced (e.g., smaller than the new solution found in Step 2). If the algorithm finds another truck that can be assigned to the second straddle carrier in order to further reduce the total distance travelled, it will do that.

Step 3. From steps 1 and 2, the assignment of two straddle carriers is developed to process all trucks so that the total distance travelled is minimized. The algorithm in this step will verify if there is another straddle carrier available. If the third straddle carrier cannot improve the solution, the algorithm will "introduce" the next straddle carriers, if available. The process will continue until the algorithm finds the next straddle carrier that can improve the solution.

If the algorithm cannot improve the solution, and all straddle carries were investigated, then the assignment of straddles to trucks is the optimal sequence of jobs that will minimize the total distance travelled.

For every available straddle carrier the process of taking over a job from the previously assigned straddle carriers is repeated. At the end, the optimal assignment of all trucks to straddle carrier(s) is developed.

The flow chart for the Heuristic with Implicit Enumeration is presented in Figure 6.7.

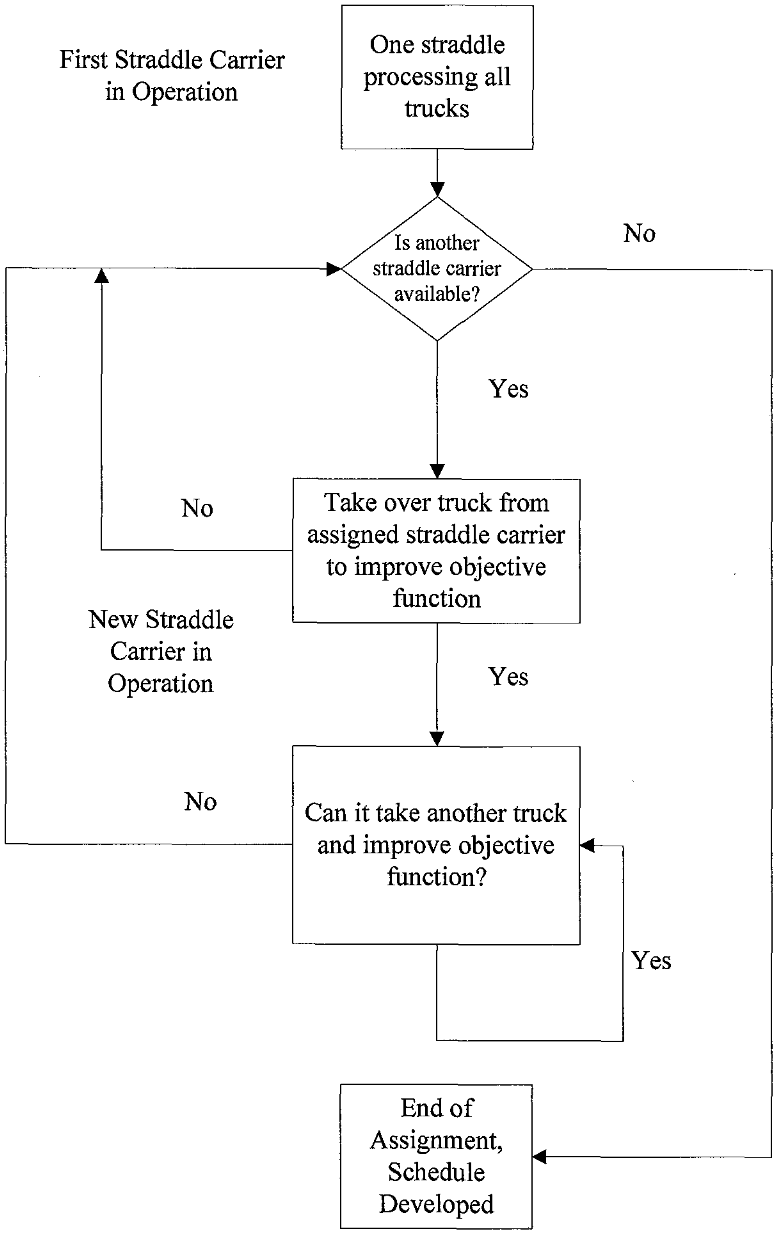


Figure 6.7 Logic of the Implicit Enumeration Heuristic

CHAPTER 7

THE APPLICATION OF STRADDLE CARRIER ASSIGNMENT MODELS

The previous chapter presented different algorithms and heuristics that will be used for the straddle carrier assignment problem. This chapter presents the container terminal layout, the truck arrival pattern, and the particulars of the Case Study to which the algorithms and heuristics will be applied. The optimal operation in terms of the planning period duration, minimum distance travelled and the related minimum optimal fleet size will be identified.

7.1 Case Study

7.1.1 Terminal Layout and Data Description

The Case Study consists of operational data from a Port of New York/New Jersey container terminal. For each truck that is arriving at the terminal (for a pick up or drop of) the following information is available:

- Arrival time at the gate
- Slot position and the time the truck arrives at the slot
- Container location in the yard (to which the container needs to be dropped off or from which it needs to be picked up)

The layout of the container terminal is illustrated in Figure 7.1. This terminal consists of three zones containing specific container blocks. Each zone consists of several blocks, and blocks are formed from a group of rows. In each row containers are stack up to three high. Each storage location has a unique identification address (e.g., TM27, TH7, etc.) which describes the position of the container.

The trucks slot area is where containers are transferred from a truck chassis to the straddle carrier and vice versa. There is a finite numbers of slots. There is a limited number of straddle carriers to serve these slots. Each truck is assigned to an empty slot, and when the truck enters the slot it is ready to be served by a straddle carrier.

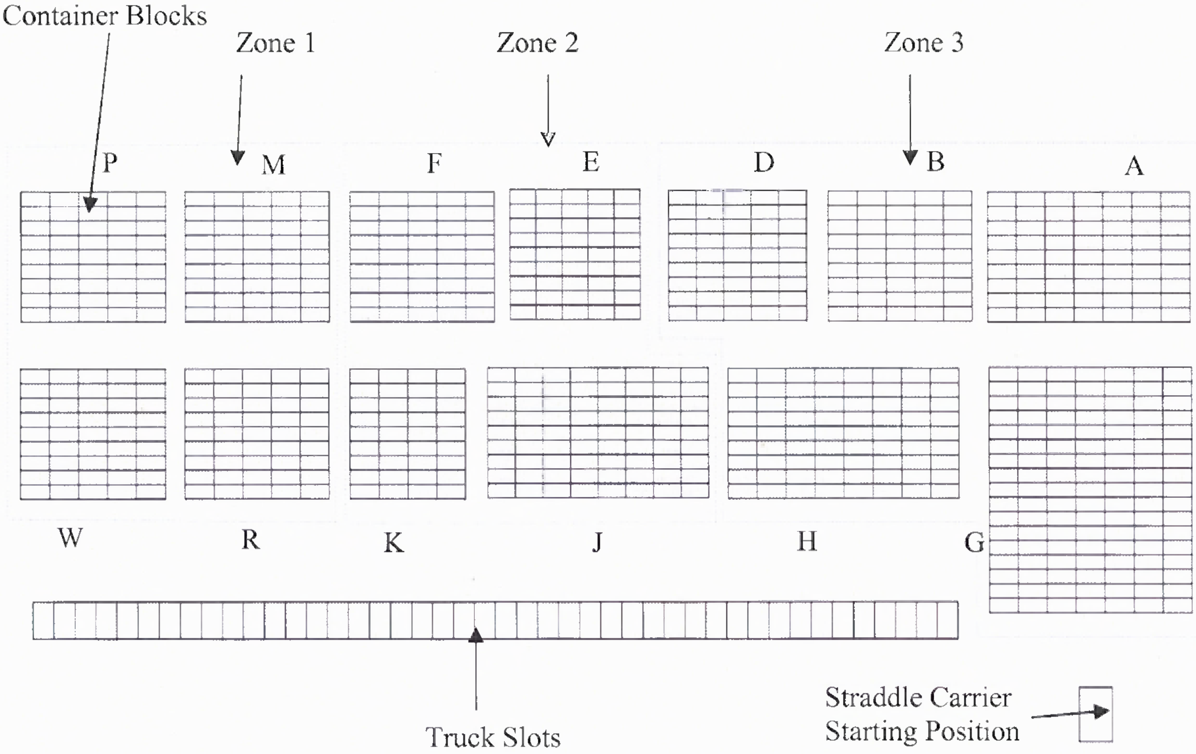


Figure 7.1 Terminal Layout

The data consist of 495 truck arrivals at the terminal and their arrival pattern is shown in Figure 7.2. The assignment is performed with a fixed straddle carrier fleet size varying from 3 to 8. The assignment models are written in the Visual Basic programming language. The programs are using as input a text file that contains truck arrival and container location information. The output results for each assignment and the related summary is saved in an MS Excel file.

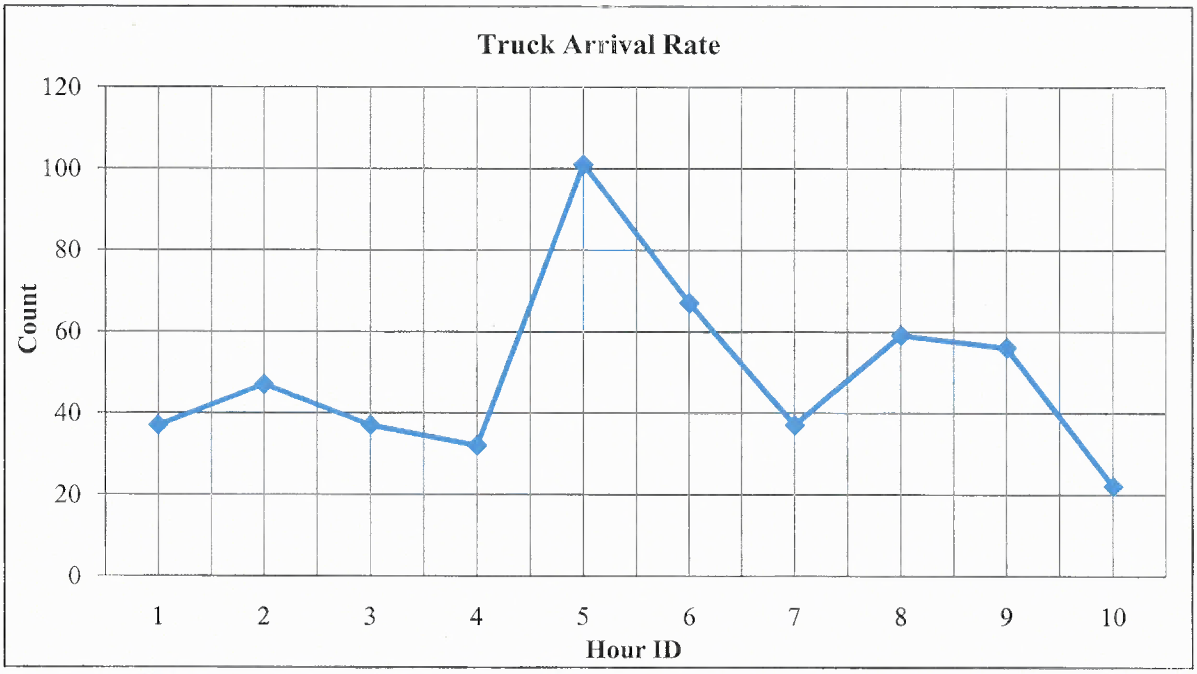


Figure 7.2 Truck arrival distribution per hour of operation

7.1.2 Assumptions

The position of a container, straddle carrier, and truck at the terminal is defined by its “x” and “y” coordinates. The straddle carrier travel path between any two points is assumed to be rectilinear and hence fixed for a defined trip. A container moves either from the storage location at the yard to the slot area or vice versa.

The straddle carriers are located at the origin point at the beginning of their assignment period. The number of straddle carriers available at any time is known and their location is also known. There are no random breakdowns and they are traveling at constant speed of a 24 mph (no traffic impacts their movement and acceleration/deceleration times are not considered).

The truck waiting time is calculated from the time the truck enters the designated slot and the time a straddle carrier begins to service it. The location of a container in the stack doesn’t influence the drop-off or pick up time.

To compare the different assignment strategies the following performance measures are calculated:

- *Distance Travelled by Straddle Carriers.* The total distance traveled is calculated as the sum of all travel itineraries that straddles completed during the operation.
- *Average Service Time.* For trucks that are picking up a container, the average service time is calculated as the time interval from the moment when straddle carrier is assigned to process that truck until a container is dropped on the truck chassis. For the truck that is bringing a container into the port, the service time is calculated as a time interval from the moment when the straddle carrier is assigned to the truck until the container is removed from the truck chassis.
- *Average Waiting Time per Truck.* This parameter is calculated as the time elapsed from the moment a truck is slotted until it is assigned to a straddle carrier.
- *Completion Time for All Jobs.* The completion time is calculated as the time elapsed from the first truck arrival until the last straddle carrier has finished with its assignment.

For each heuristic, the performance measures are calculated and heuristics will be compared to each other to determine the best approach for reaching the objective of the dissertation. The initial solution, the baseline algorithm, will be based on FCFS rule and other implemented algorithms will try to improve upon this solution.

7.2 Case Study Results

7.2.1 First Come First Served

The optimal results for a given straddle carrier fleet size are shown in Table 7.1. The performance measures are presented as rows and the straddle carrier fleet size is shown as columns.

Table 7.1 Results of the Application of FCFS Rule

	Straddle Carrier Fleet Size					
	3	**4**	**5**	**6**	**7**	**8**
Average Waiting Time Per Truck (hh:mm:ss)	0:51:22	0:15:25	0:06:11	0:02:10	0:00:41	0:00:38
Average Service Time per Truck (hh:mm:ss)	0:54:16	0:18:34	0:09:21	0:05:12	0:03:28	0:03:29
Average Service Time per Drop-Off Truck (hh:mm:ss)	1:27:39	0:20:14	0:02:17	0:03:09	0:02:09	0:01:39
Average Service Time per Pick-Up Truck (hh:mm:ss)	0:40:01	0:18:13	0:10:00	0:05:29	0:03:40	0:03:44
Time needed to process all jobs (hh:mm:ss)	12:02:01	10:13:01	10:13:01	10:11:17	10:11:17	10:11:17
Total Distance Travelled by Straddle Carriers (miles)	651.42	665.64	646.38	632.97	587.82	596.67

7.2.1.1 Discussion of Results

From Figure 7.3 it is apparent that the optimal solution in terms of minimizing the straddle travel distance is obtained by running seven straddle carriers. The total distance travelled by seven straddle carriers is 587.82 miles. The average truck wait time is 41 seconds. The time elapsed until all trucks are processed is 10 hours, 11 minutes and 17 seconds.

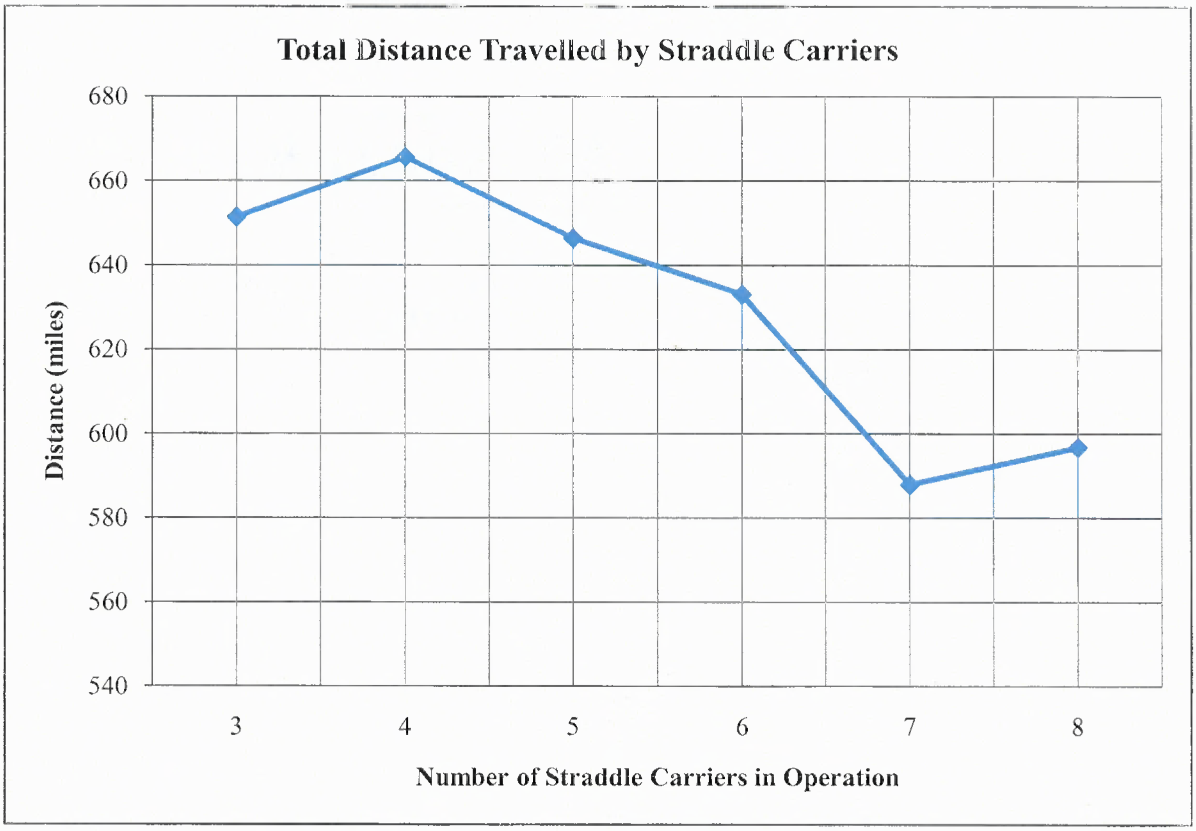


Figure 7.3 Total distance travelled as a function of straddle carrier fleet size

The time needed to process varies by less than 2 minutes when more than four straddle carriers are in operation (Table 7.1). This means that five straddle carriers may be sufficient to process all trucks on time. When five instead of eight straddles are used, the truck delay would increase from 41 seconds to 6 minutes 11 seconds, which in relative terms may not be much of a difference, while the cost of "saving" two straddles may be significant. The following question of the trade-off between service quality to trucks and reduced capital cost to the operator can be postulated by the operator: "What is the straddle carrier fleet size that I can run that minimizes my cost while keeping a satisfactory level of service for trucks in terms of acceptable service time?" It can be seen from Figure 7.4 (and Table 7.1), that the average truck service time when five straddle carriers are operating is larger by almost 6 minutes compared to the average service time when seven straddle carriers are in operation.

The change in average service time per truck and average waiting time per truck as function of straddle carrier fleet size is shown in Figures 7.4 and 7.5 respectively.

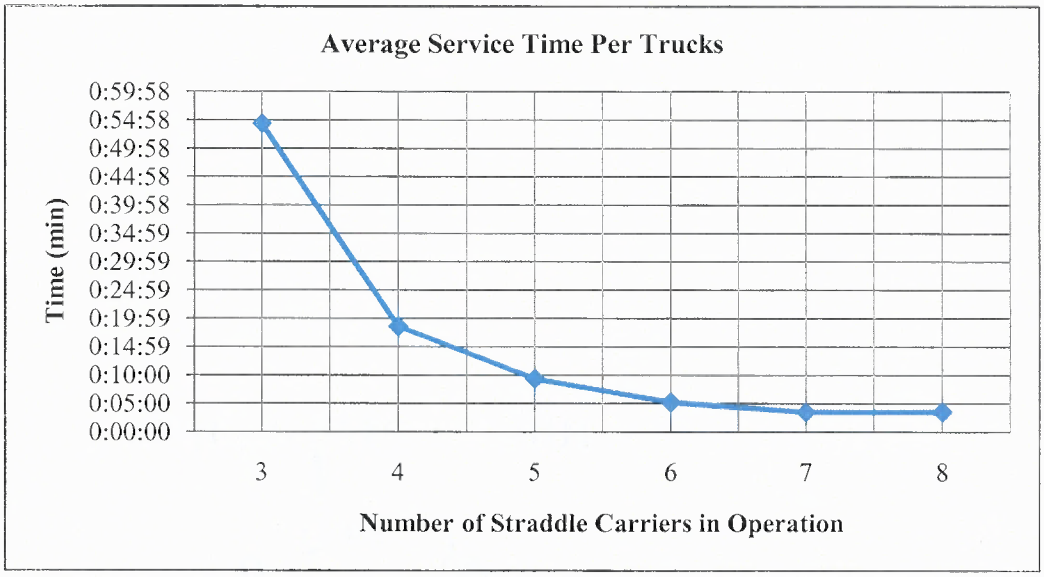


Figure 7.4 Average service time per truck

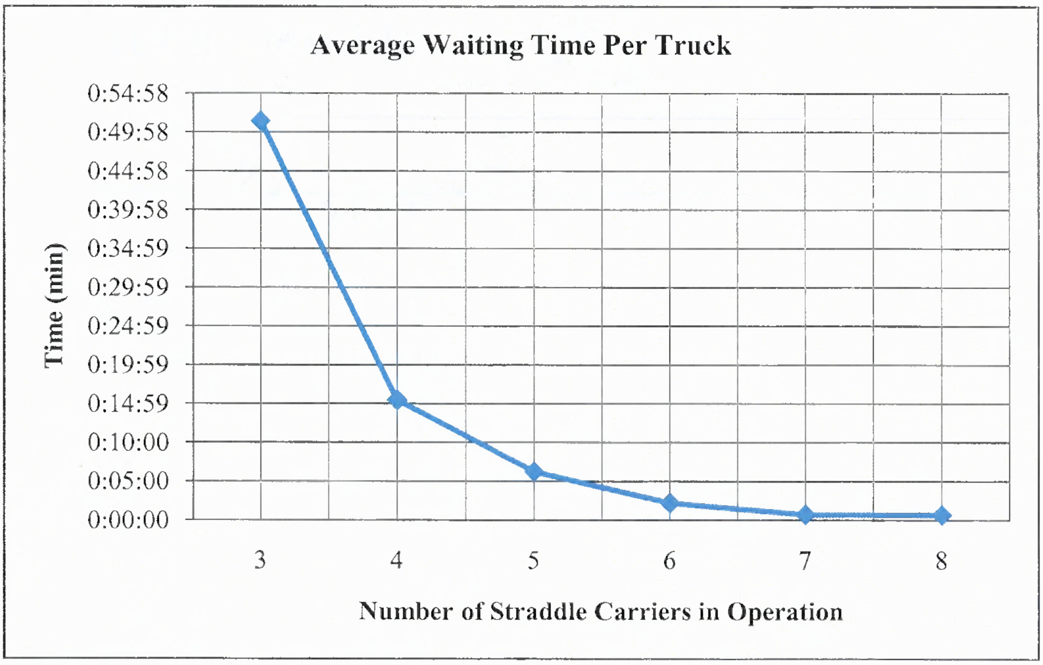


Figure 7.5 Average waiting time per truck

7.2.1.2 The Anomaly

An interesting anomaly is revealed in Figure 7.3. If the operation is carried out with eight straddles and then one straddle is removed one would expect that the remaining straddles would travel longer distances to accomplish the same amount of work. In fact, the opposite is true: removing a straddle reduces the total distance travelled. This result can be explained in the following way: Having more straddle carriers in operation than it is needed does not result in the optimal operation. Furthermore, the opposite is true – having more straddles than it is needed will result in an inefficient operation. The root cause of this inefficiency is an uncoordinated competition among the straddles for trucks (containers). In this competition, the straddles are stealing loads from each other thus destroying the matching opportunities that would lead to the minimization of travelled distance. The removal of a straddle increases the chances of a match as it is shown in the reduction in mileage.

Similarly, by having more available straddles than needed, it means that a straddle may be assigned to a truck whose service can lead to a longer travel distance. Leaving the truck to wait and be assigned by a different straddle at a later time may result in a better assignment in terms of reduced distance travelled.

7.2.2 Hungarian Assignment I Results

The previous section alluded to the fact that by postponing the assignment of straddles to trucks a tangible savings in terms of reduced mileage travelled can be achieved. Furthermore, a further savings in straddle carrier fleet size can be obtained without a significant deterioration in truck service time. The source of this efficiency is explored in this algorithm.

7.2.2.1 Discussion of Results

The results in Figure 7.6 show that the optimal solution is obtained when five straddle carriers are in operation and the planning period is seven minutes.

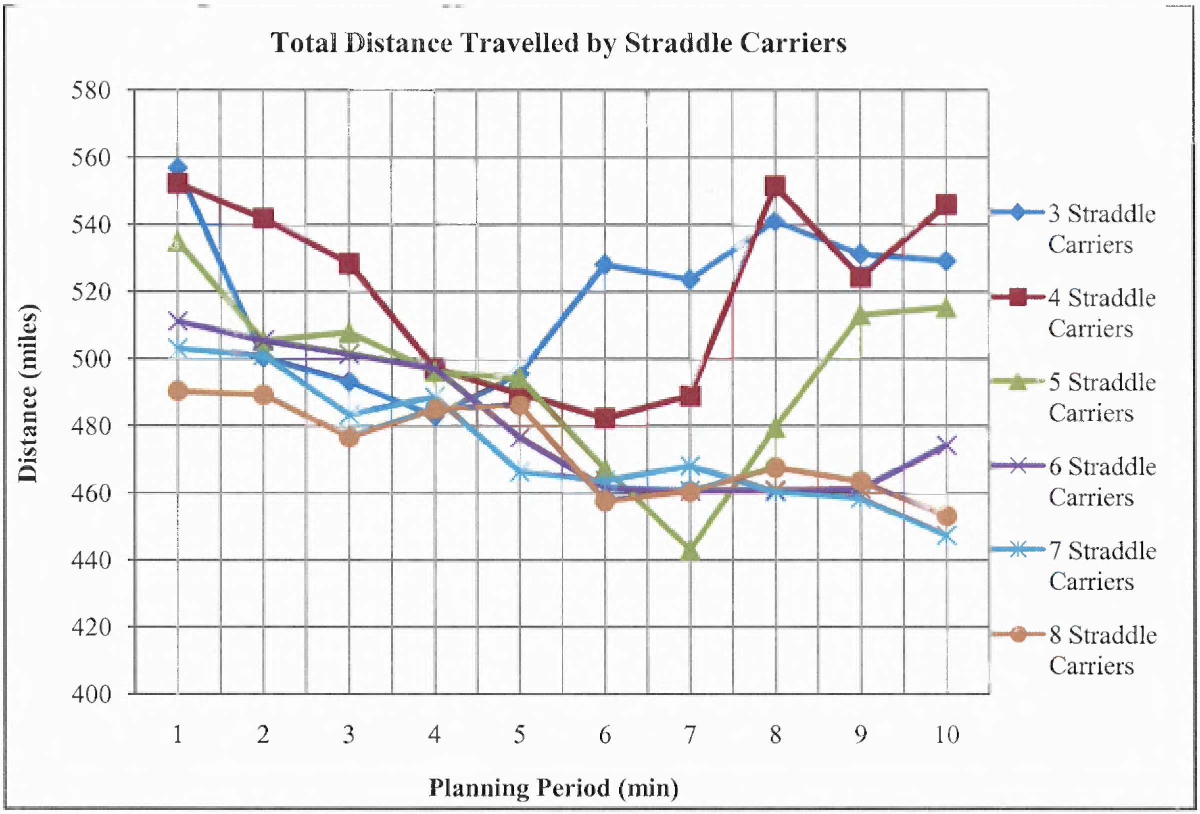


Figure 7.6 Total distance travelled by straddle carriers

The average truck waiting time, shown in Figure 7.7, increases with the duration of the planning period. As more trucks have arrived and are in the queue, there are more opportunities for straddle carriers, and better (least distance travelled) matches of straddles with trucks can be made if fewer straddles are available for the assignment. Since there is no limit on the maximum allowed waiting time, straddle carriers do not have any priority assignments based on the waiting time constraint. The lack of the constraint results in excessive waiting times for some trucks because they might be far away in the yard and can only be assigned if there is an available carrier that does not have any other (better) trucks to choose from.

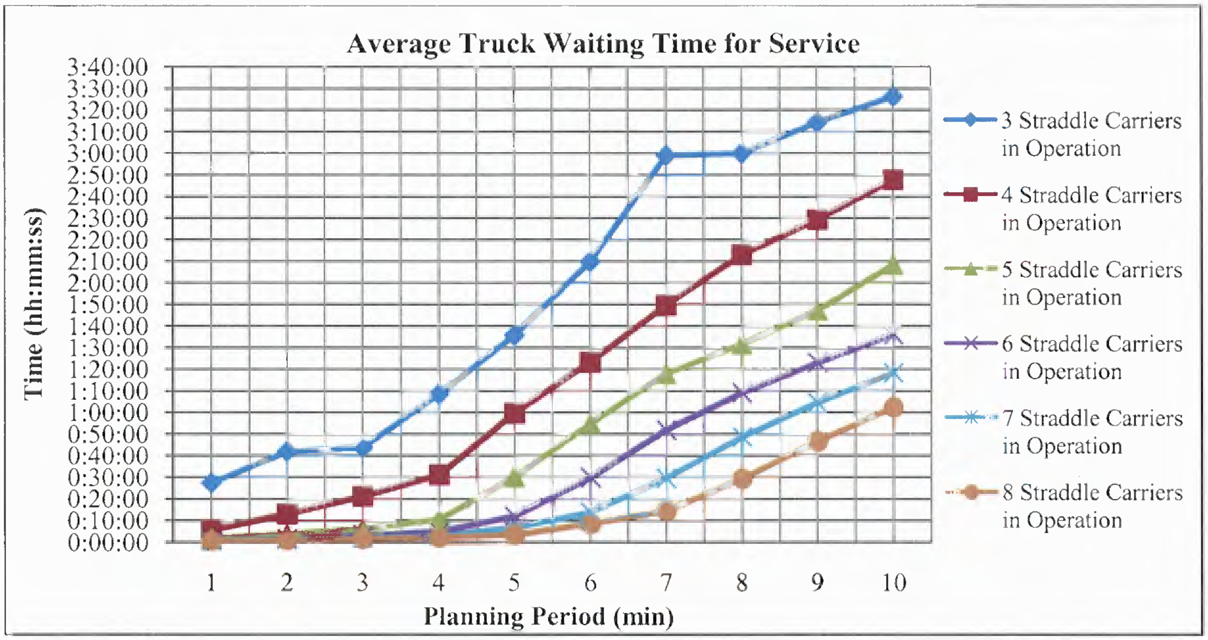


Figure 7.7 Average truck waiting time for service

Figure 7.8 shows that the total time required to process all trucks is also a function of the planning period. As the planning period length is getting increased, the average waiting time of trucks is also increased. Straddle carrier total operational time is starting to increase at a higher rate for certain values of the planning period.

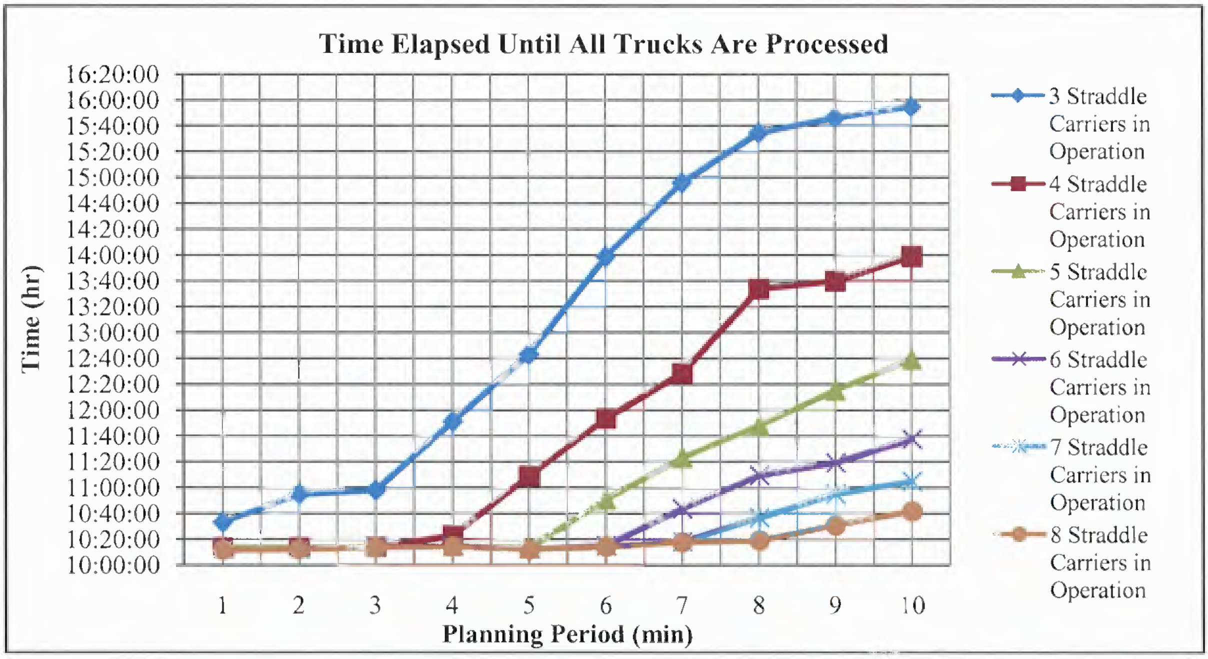


Figure 7.8 Time elapsed until all trucks are processed

7.2.2.2 The Anomaly Remains

The anomaly encountered in Section 7.2.1.2 with the heuristic using the FCFS Rule, clearly occurs in this case as well. Having a larger number of straddle carriers in operation is resulting in a worse solution in terms of the total distance travelled. To illustrate this point, having three straddle carriers and a four- minute planning period yields a shorter total travel distance compared to the case of eight straddle carriers dispatched for the same planning period. If the planning period is between eight and 10 minutes the operation with seven straddle carriers has better results in terms of distance travelled than the operation with eight straddle carriers.

7.2.3 Hungarian Assignment II Results

The results are shown in Figure 7.9. The optimal solution is achieved with 8 straddle carriers and a nine- minute planning period.

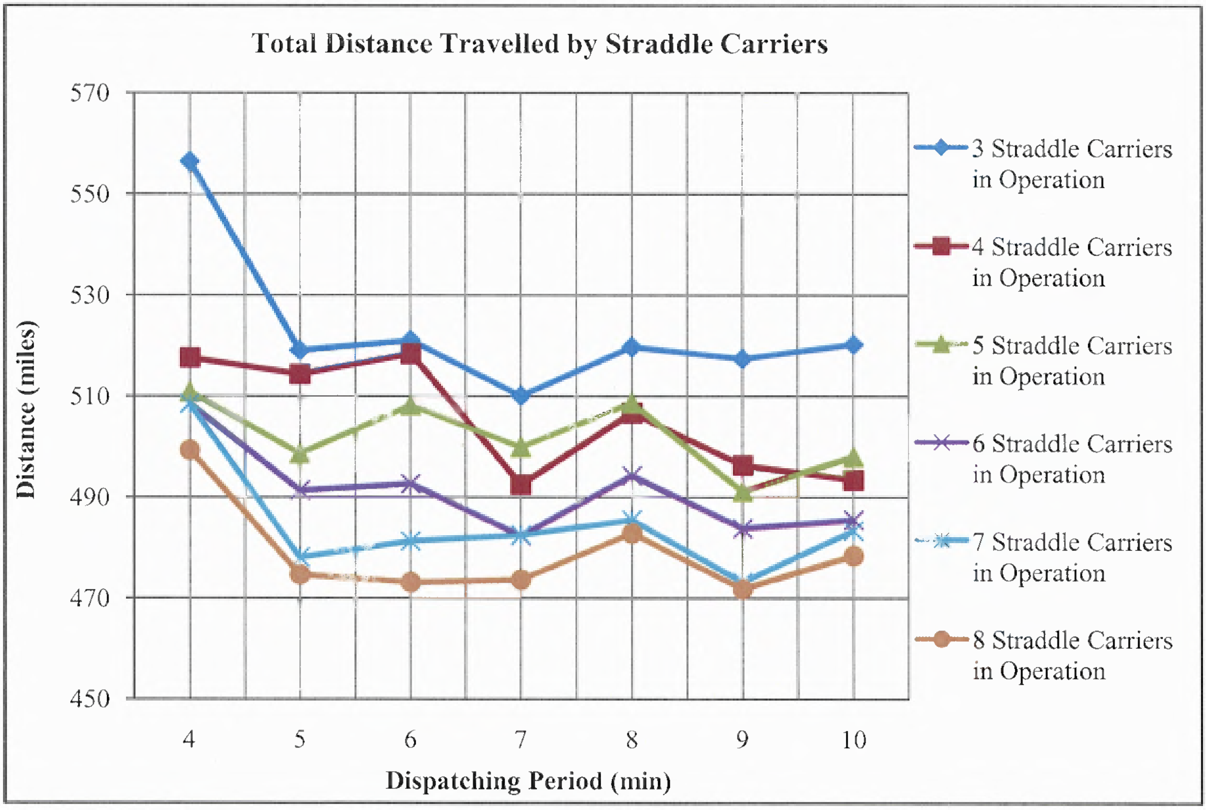


Figure 7.9 Total distance traveled by straddle carriers

Should the terminal operator decide to run the operation with one less straddle and with the planning period of nine minutes, the total distance travelled will increase marginally by only 0.265% or 1.25 miles. This will be accompanied by insignificant increase in average truck waiting time (from 5:01 minutes to 5:08 minutes) as shown in Figure 7.10.

If the terminal operator would like to reduce the waiting time of trucks even more, he can operate with seven straddle carriers with a five-minute planning period which will reduce the truck waiting time by 25.91% (reduction of waiting time from 5:01 minutes to 3:43 minutes). This will result in an increase in the total distance travelled by only 1.296%.

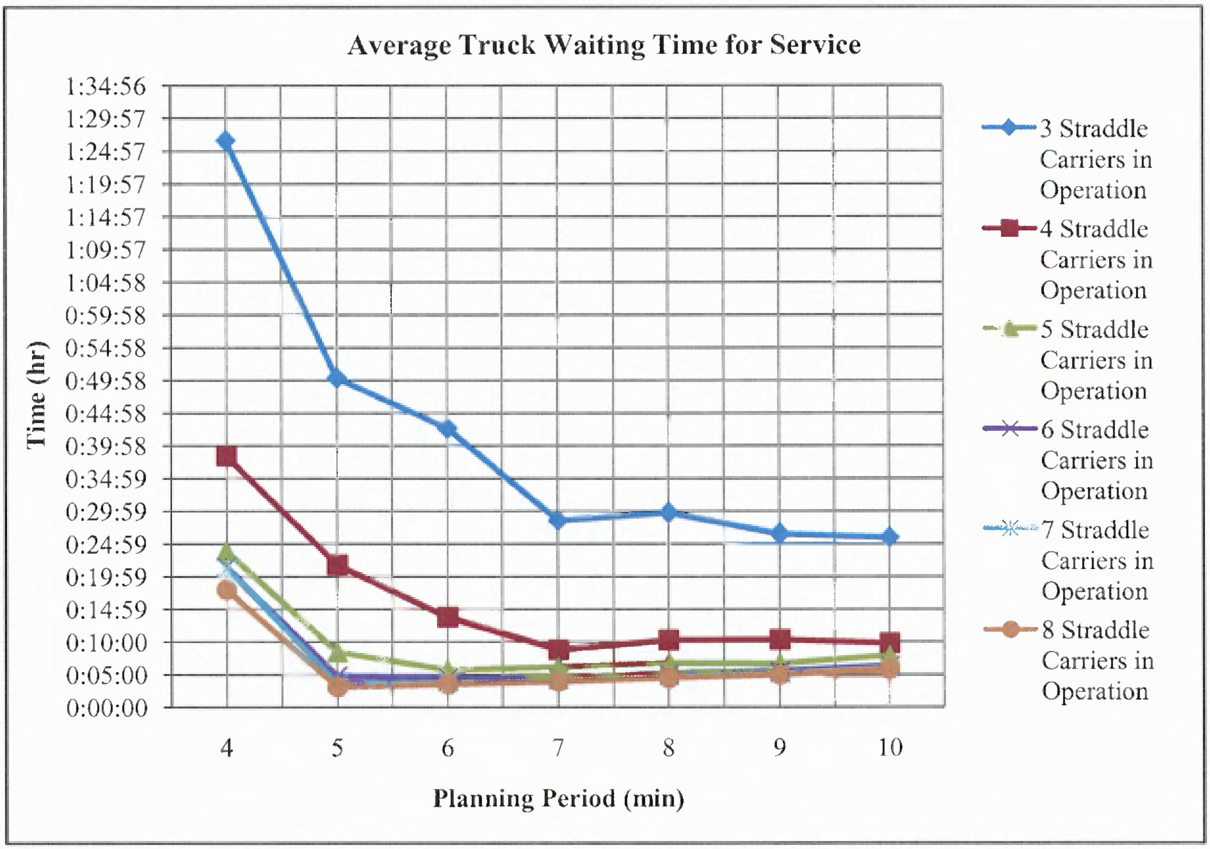


Figure 7.10 Average truck waiting time for service

The average time that trucks wait for service does not differ substantially, if there are seven or eight straddle carriers in operation. Waiting time reaches the minimum of 3:10 minutes for eight straddles in operation and for a 5-minute planning period. That is 36.88% less compared to the waiting time when the total distance travelled reaches minimum.

Figure 7.11 shows the time required to process all trucks. The time elapsed is significantly different only when three straddle carriers are in operation. It shows that the operation has significant delays in processing trucks. As the planning period increases to more than six minutes, the time required to process all trucks is the same for four straddle carriers and above. This means that extending the work hours at the terminal to process all trucks is not required.

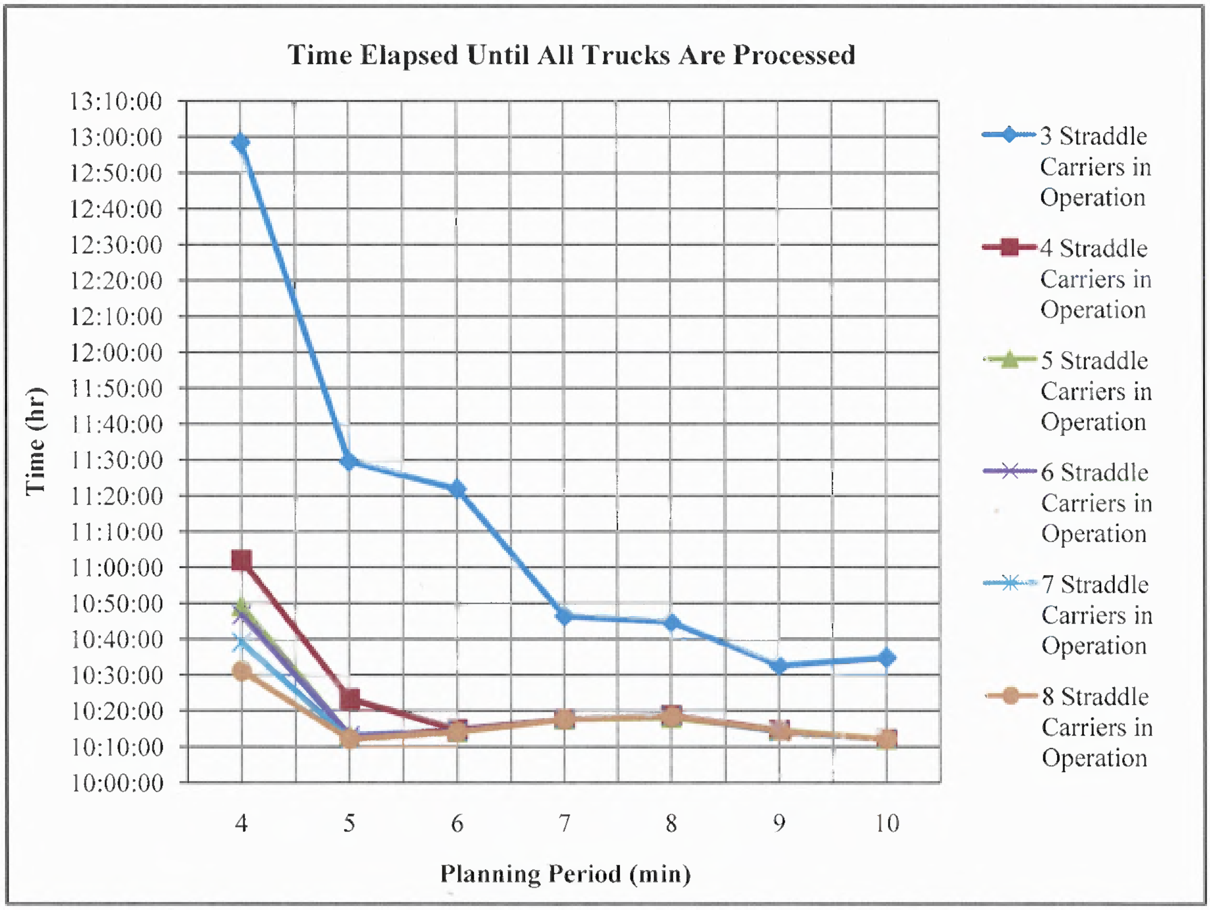


Figure 7.11 Time elapsed until all jobs are processed

7.2.4 Implicit Enumeration Heuristic Results

The total travel distance for a given straddle carrier fleet size and various planning periods is shown in Figure 7.12. The figure shows that the optimal solution is achieved with six straddle carriers and a planning period of three minutes. The average wait time is 13:43 minutes. The time required to process all trucks is 10:13:40 hours (Appendix A, Table A.16).

The assignment with eight straddle carriers in operation and a 8-minute planning period has 0.2% longer travel distance compared to the best solution achieved. The average truck waiting time is reduced by 19.23%.

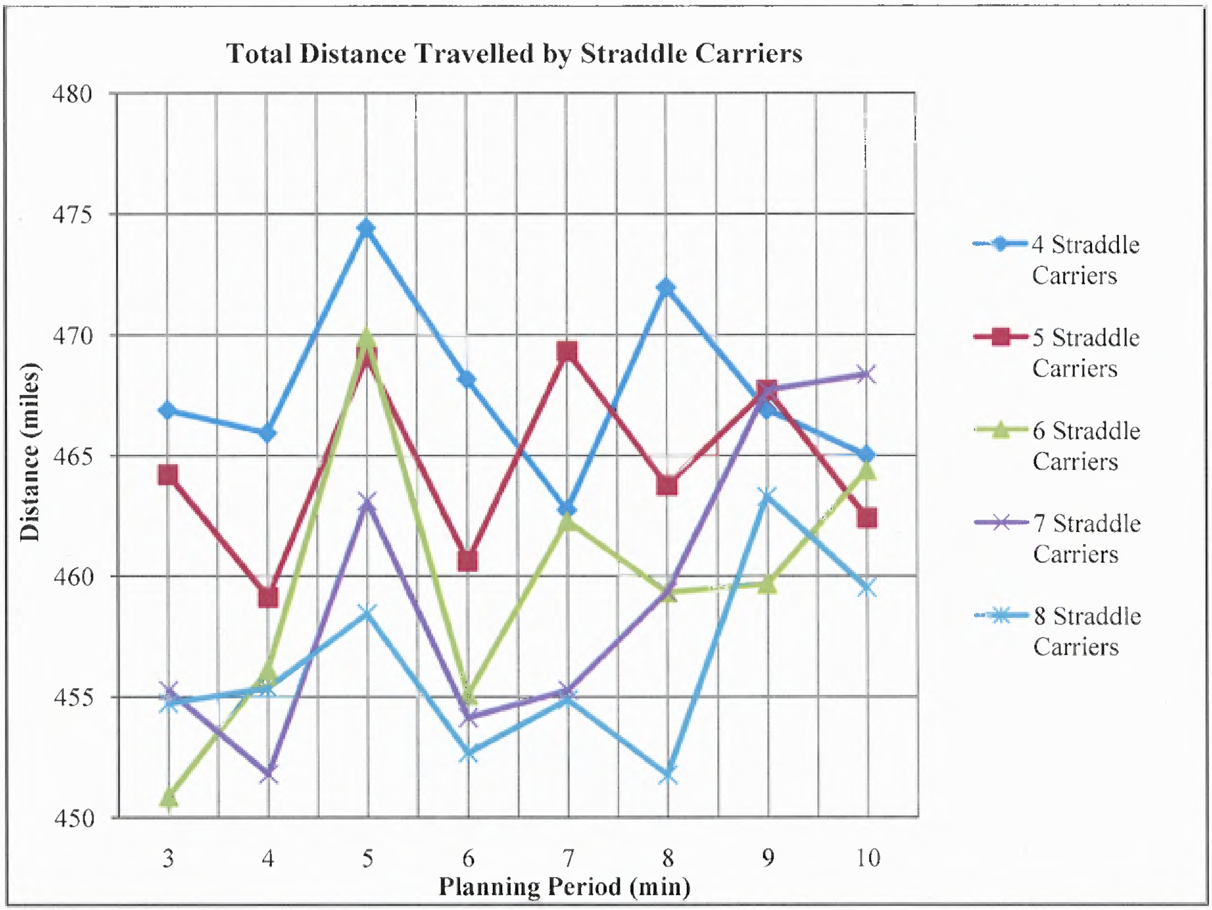


Figure 7.12 Total distance travelled as a function of the straddle carrier fleet size and the planning period

The second best solution has eight straddle carriers in operation and a planning period of eight minutes. Even if this result is used as a possible solution, from the graph we can observe that the assignment with a seven straddle carriers and with the four-minute planning period differs only by 0.93 miles, which is 0.0096% more, but reduces the average truck waiting time by 4.81%. This solution is preferred by both the terminal operator and the truckers because it yields lower cost (by reducing the equipment pool by one straddle carrier (12.5%)) and the trucks are waiting less for service.

An optimal solution with less equipment in operation enables terminal operator to assign excess equipment to other parts of the terminal (in the short planning horizon) or to remove (and sell the equipment in the long run) and reduce the capital cost.

Figure 7.13 shows the average waiting time for different straddle carrier fleet size and planning period.

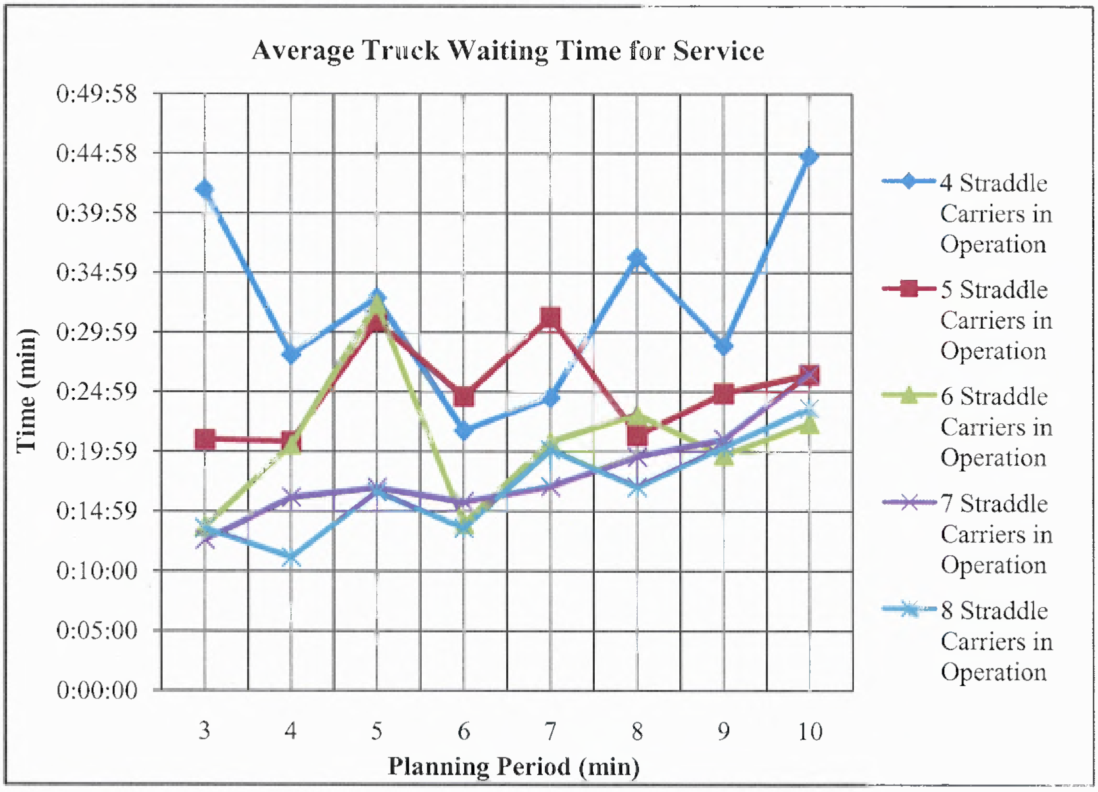


Figure 7.13 Average truck waiting time for service

When the number of straddle carriers in operation is more than four, Figure 7.14 shows that the time required to process all trucks is similar. Only when four straddle carriers are in operation and the planning period is either 3 or 10 minutes, there is a significant difference in the time required to process all trucks.

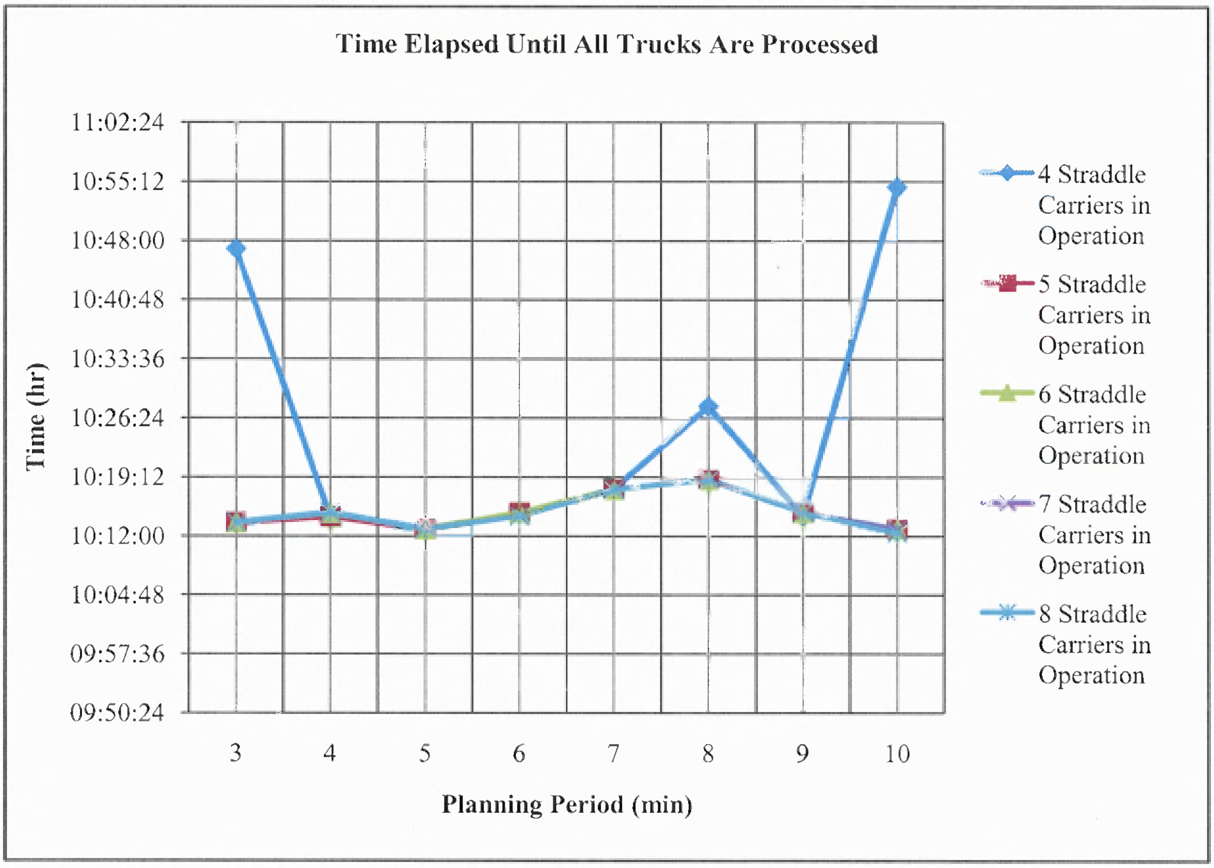


Figure 7.14 Time elapsed until all trucks are processed

7.3 Comparison Between Heuristics

The optimal solution for each heuristic is shown in Table 7.2. The best solution in terms of the total distance travelled by straddle carriers is obtained with Hungarian I. The solution uses five straddle carriers and a seven-minute planning period. The solution results in 25%, 35% and 12.5% equipment reduction when compared to the FCFS, Hungarian II and the Implicit Enumeration Heuristic respectively.

The total distance travelled is reduced by 24.66% when compared to the FCFS solution. The average truck waiting time increased substantially when compared to other heuristics.

Table 7.2 Optimal Solution from Four Heuristics

	FCFS	Hungarian I	Hungarian II	Implicit Enumeration Heuristic
Straddle Carrier Fleet Size	7	5	8	6
Planning Period (min)	-	7	9	3
Average Waiting Time Per Truck (hh:mm:ss)	0:00:41	1:17:47	0:05:01	0:13:43
Average service time for trucks (hh:mm:ss)	0:03:28	1:19:48	0:07:15	0:15:51
Average service time for drop-off trucks (hh:mm:ss)	0:02:09	0:38:09	0:05:06	0:12:56
Average service time for pick-up trucks (hh:mm:ss)	0:03:40	1:28:23	0:07:31	0:16:13
Time needed to process all jobs (hh:mm:ss)	10:11:17	11:23:02	10:14:25	10:13:40
Total Distance Travelled by Straddle Carriers (miles)	587.82	442.95	471.84	450.87

Hungarian II managed to reduce the waiting time significantly to 5 minutes and 1 second. Also, instead of having five straddle carriers in operation to achieve the optimal solution, eight straddle carriers are needed to be in operation to minimize the total distance travelled. Compared to the FCFS, Hungarian II reduced the total distance travelled by 19.73%. This is a 6.12% increase compared to Hungarian I.

The Implicit Enumeration Heuristic increased the total distance travelled by 4.44% compared to Hungarian I and decreased it by 4.439% and 23.29% compared to Hungarian II and FCFS respectively. The Heuristic has increases the total distance travelled by 1.789% when compared to Hungarian I. The average truck waiting time is 13 minutes and 43 seconds which is acceptable for a large container terminal. The average truck waiting time for service increased compared to the FCFS and Hungarian II. Also, the optimal operation using Implicit Enumeration Heuristic was achieved with a reduction of 25% in straddle carrier fleet size compared to the Hungarian I and by 12.5% compared to the FCFS. Since this algorithm minimizes the distance travelled by straddle carriers during each assignment, the priority is given to straddle carriers, not trucks. The algorithm only prioritizes the trucks if they have exceeded the maximum allowed waiting time constraint.

The results show that by introducing a planning period and thus taking advantages of known truck-container pairs will provide a better allocation of straddle carriers to trucks. It is clear that a fleet size of 5 straddle carriers and a 7-minute planning period gives the best results in terms of minimizing the total distance travelled by straddle carriers. But, since the nature of the algorithm did not force straddle carriers to process trucks that are waiting for a long period of time, the average waiting time in not acceptable for a trucker. Thus, the Implicit Enumeration heuristic provides an acceptable solution in terms of waiting time for trucks. The recommendation is to use 6 straddle carriers and a 3- minute planning period and thus provide a significantly better service to trucks with a minimal increase in total travel distance by 4.44%.

CHAPTER 8

SENSITIVITY OF THE STRADDLE CARRIER FLEET SIZE AND THE PLANNING PERIOD DURATION WITH RESPECT TO THE TRUCK ARRIVAL RATE

This chapter presents an analysis of how the straddle carrier fleet size and the duration of the planning period are impacted by different truck arrival rates. For a specific arrival rate, the analysis determines the optimal straddle carrier fleet size that needs to be deployed, and the optimal planning period. The generation of sample data is explained next followed by the discussion of results.

8.1 Generating the Sample Data

To determine the relationship between the truck arrival rate, the straddle carrier fleet size and the duration of the planning period, a series of experiments were conducted. In each experiment, the straddle carrier fleet size and the duration of the planning period were calculated for a particular truck arrival rate. Truck arrival at the slots is represented by the Poisson process[3]. The inter-arrival times between events in the Poisson process are described by the exponential distribution.

The Monte Carlo technique was used to sample random variables. Monte Carlo sampling assumes a "random number generator", which generates uniform statistically independent values on the half open interval [0, 1) (Particle Data Group, 2008).

The truck inter-arrival time is obtained from the inverse function of the cumulative distribution function for the Exponential distribution, $F(t, \lambda)$, where t is the truck inter-arrival time and λ is truck arrival rate.

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[3] In Poisson process events occur continuously and independently of one another

The methodology is presented below:

$$F(t, \lambda) = P(X<t) = 1 - e^{-\lambda t}$$

$P(t)$ is a random variable which will occur with uniform probability density on [0,1]. The truck inter-arrival time t, can be derived from the inverse function of P.

$$P = 1 - e^{-\lambda t}$$

$$lnP = -lne^{-\lambda t}$$

$$lnP = \lambda \cdot t$$

$$t = \frac{1}{\lambda} \cdot lnP \tag{8.1}$$

Microsoft Excel's random number generator is used to generate the random truck arrival time based on equation (8.1).

The truck arrival rate (number of trucks arriving during one hour), the straddle carrier fleet size and the length of the planning period in each simulation are presented in Table 8.1 on next page. For example, for a truck arrival rate of 25 trucks/hour, the straddle carrier fleet size was varied from 3 to 8, while the planning period was varied from 1 to 10 minutes. Thus, the first scenario for the truck arrival rate of 25 trucks/hour had 3 straddle carriers in operation while the planning period was 1 minute. The second scenario had the same truck arrival rate and straddle carrier fleet size, but had a planning period of 2 minutes. The process continues until all combinations are simulated. There was a total of 2,800 scenarios to simulate. Trucks were arriving during a 10 hour period with 90% of trucks arrived to pick-up containers from the terminal, while 10% delivered containers to the terminal. The truck slot location and the container that is associated with that particular truck were also randomly generated. The Hungarian Algorithm I was used to solve the assignment problem.

Table 8.1 Simulation Scenario Structure

Truck Arrival Rate (trucks/hour)	25	50	75	100	125
Straddle Carrier Fleet Size	From 3 to 8	From 5 to 10	From 6 to 12	From 8 to 14	From 10 to 16
Planning Period	From 1 to 10 minutes	From 1 to 10 minutes	From 1 to 10 minutes	From 1 to 10 minutes	From 1 to 10 minutes
Number of different demand sets	10	10	10	10	10
Total number of simulations for specific arrival rate	(8-3)*10*10 = 500	(10-5)*10*10 = 500	(12-6)*10*10 = 600	(14-8)*10*10 = 600	(16-10)*10*10 = 600
Total number of simulations	500+500+600+600+600 = 2800				

8.2 Cost of Straddle Carrier Operation

For a specific truck arrival rate, the optimal straddle carrier fleet size and the optimal planning period is determined based on the total daily cost of operation. The cost associated with processing trucks after the end of the 10 hours of operation is higher because it is considered to be overtime.

The total daily cost of operation (in $ per day) consists of the straddle carrier ownership and operating costs. The Straddle Carrier ownership is expressed by equation (8.2).

$$C_o = \frac{P \cdot CRF}{n} \tag{8.2}$$

Where:

P - Purchase price (in $s)

CRF – Capital Recovery Factor and is expressed by equation 8.3

n – Useful life (in years)

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \tag{8.3}$$

Where:

i - Interest (discount) rate

The straddle carrier purchase price is assumed to be $ 1,000,000. The expected service life is 15 years (Port of Tacoma, 2008) and there is zero salvage value at the end of the service life. The Capital Recovery Factor (CRF) which converts a present value into a stream of equal annual payments over 15 years at a 5.55% interest (discount) rate is:

$$CRF = \frac{i \cdot (1+i)^n}{(1+i)^n - 1} = 0.099625$$

The cost of owning straddle is then $99,626 per year. Assuming that the terminal operates 260 days per year, and ignoring the daily compounding of interest, the daily ownership cost is $383.18 per straddle.

The variable cost consists of operator wages, straddle carrier maintenance and wear and tear, and the cost of fuel and electricity. The variable cost is expressed by equation (8.4):

$$C_v = C_s + C_{op} + C_f \tag{8.4}$$

Where:

C_s - Operator wage

C_{op} – Maintenance and wear and tear

C_e - Energy cost (fuel, electricity, etc.)

The operator wage is based on an annual salary of $ 100,000 per year, 260 workdays per year. The wage rate is $ 38.462 per hour during regular hours of operation and 57.69 $/h for overtime. Union rules dictate that there must be three drivers for every two straddles, thus the wage portion of a straddle's operating cost is multiplied by 1.5.

The maintenance of the straddle carrier during operation and wear and tear of tires, cables etc., is assumed to be 10 $/mile.

The straddle carrier cost of fuel and electricity is 4.2 $/mile. The total cost of energy is calculated as a total number of miles travelled by a straddle carrier during the day multiplied by the energy cost of 4.2 $/mile.

8.3 Simulation Analysis

The optimal straddle carrier fleet size and the planning period resulting from the simulation run are given in Table 8.2. For each specific arrival rate there are ten different simulation outputs based on ten different scenarios. The results are averaged across the scenarios. For example, the least cost operation for a truck arrival rate of 25 trucks/hour involves on average three straddle carriers and a five-minute planning period, yielding an average cost of $8,754.79 per day. The remaining optimal fleet size and planning period, the cost and selected performance measures for the arrival rates ranging from 25 truck/hour to 125 trucks/hour are shown in the table. Detailed results are given in Appendix 8.4.

Table 8.2 Optimal Planning Period, Straddle Carrier Fleet Size and Performance for Different Arrival Rates

Arrival Rate (trucks/hour)	25	50	75	100	125
Straddle Carrier Fleet Size	3	6	8	10	13
Planning Period (min)	5	4	2	2	2
Average truck waiting time for service (hh:mm:ss)	00:06:03	00:03:10	00:02:11	00:01:47	0:01:13
Average service time per truck (hh:mm:ss)	00:09:47	00:06:40	00:05:50	00:05:20	0:04:38
Average service time for drop-off truck (hh:mm:ss)	00:04:57	00:03:16	00:02:09	00:02:01	0:01:40
Average service time for pick-up truck (hh:mm:ss)	00:10:25	00:07:04	00:06:14	00:05:43	0:04:57
Time Needed To finish all jobs (hh:mm:ss)	10:04:07	10:07:31	10:09:21	10:05:12	10:05:47
Total Distance Travelled by Straddle Carriers (miles)	386.56	764.90	1168.53	1511.01	1824.26
Total Cost of Operation Per Day ($/day)	8,754.79	16,722.85	24,381.66	31,132.17	38,494.37

By doubling the arrival rate from 25 to 50 trucks per hour, the optimal straddle carrier fleet size also doubled (from 3 to 6) and the planning period was reduced from 5 to 4 minutes. As the arrival rate increased, in general, as shown in Table 8.2 and Figure 8.1, the number of straddle carriers in operation also increased. To accommodate a higher number of requests for service, the duration of the planning period was reduced.

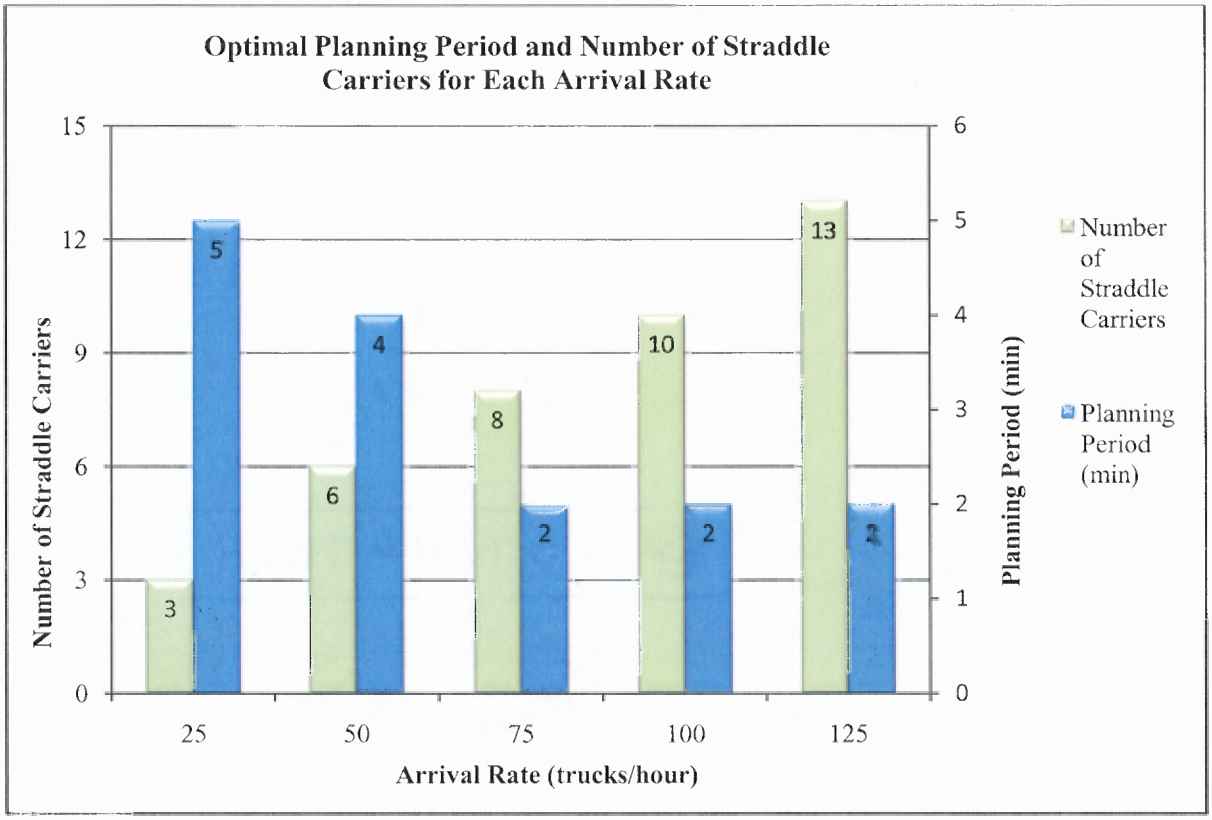

Figure 8.1 Optimal planning period and straddle carrier fleet size for different truck arrival rates

8.4 Impact of Load Imbalance

To evaluate the impact of split between import and export containers arriving at the terminal, an experiment was conducted. In this experiment, the truck arrival rate was 100 trucks per hour, and the percentage of import containers varied between 10 and 80%. Figure 8.2 shows that the minimum cost is achieved when the operation is perfectly balanced. In this operation, 50% of trucks are coming to pick up import containers and 50% are arriving to deliver export containers.

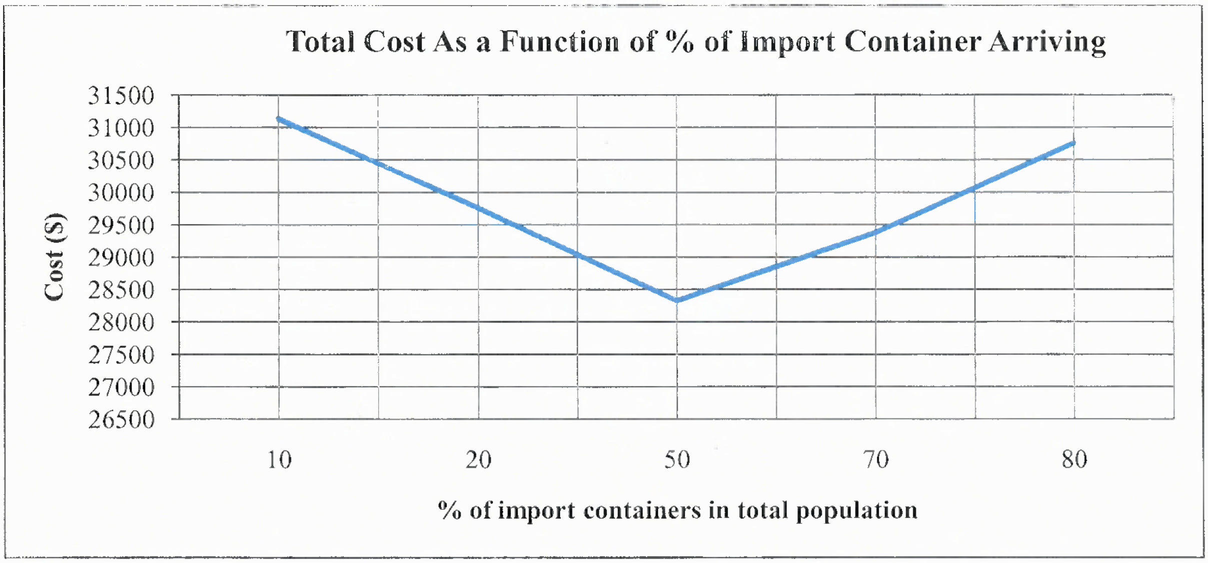

Figure 8.2 Total daily cost as a function of percentage of import trucks arriving at the terminal

However, the straddle carrier fleet size and planning period are not sensitive to the load imbalance (distribution of import and export trucks) as shown in Table 8.3. The straddle carrier fleet size remains fixed at 10 straddles and the planning period is 2 minutes.

Table 8.3 Optimal Straddle Carrier Fleet Size and Planning Period as a Function of Import Trucks Arriving at the Terminal

	Optimal Assignment		
Distribution	Straddle Carriers Fleet Size	Planning Period	Total Daily Cost
90% imports 10% exports	10	2	$ 31,132.17
80% imports 20% exports	10	2	$ 29,753.39
50% imports 50% exports	10	2	$ 28,317.77
30% imports 70% exports	10	2	$ 29,367.94
20% imports 80% exports	10	2	$ 30,751.92

8.5 Economies of Scale in Straddle Operation

Table 8.4 shows a change in the optimal cost of operation and the straddle carrier fleet size needed when the arrival rate changes. There are economies of scale present in terms of costs. As the arrival rate increases by 100% (to 50 trucks/hr), the cost of operation is increased only by 91%. If the arrival rate is further increased to 75 trucks/hr (200% increase compared to the initial case) the total cost is increased by 178%. This trend is observed in the straddle carrier fleet size as well. When the arrival rate is doubled, the total number of straddles also doubled, and when the arrival rate triples, the straddle carrier fleet size increases by 167%.

Table 8.4 Change

Arrival Rate (trucks/hour)	25	50	75	100	125
Increase in truck arrival rate (%)		100%	200%	300%	400%
Increase in cost of operation (%)		91%	178%	281%	340%
Increase in equipment (%)		100%	167%	233%	333%

If the cost of operation is expressed using the average cost per container, the results are shown in Table 8.5 and Figure 8.3. This result show that the average costs are decreasing. This means that the higher the number of request for service, the lower the level of investment for each truck processed.

Table 8.5 Average Cost per Container

Arrival Rate (trucks/hour)	25	50	75	100	125
Average Cost per Container ($/container)	$ 35.02	$ 33.45	$ 32.51	$ 31.13	$ 30.80

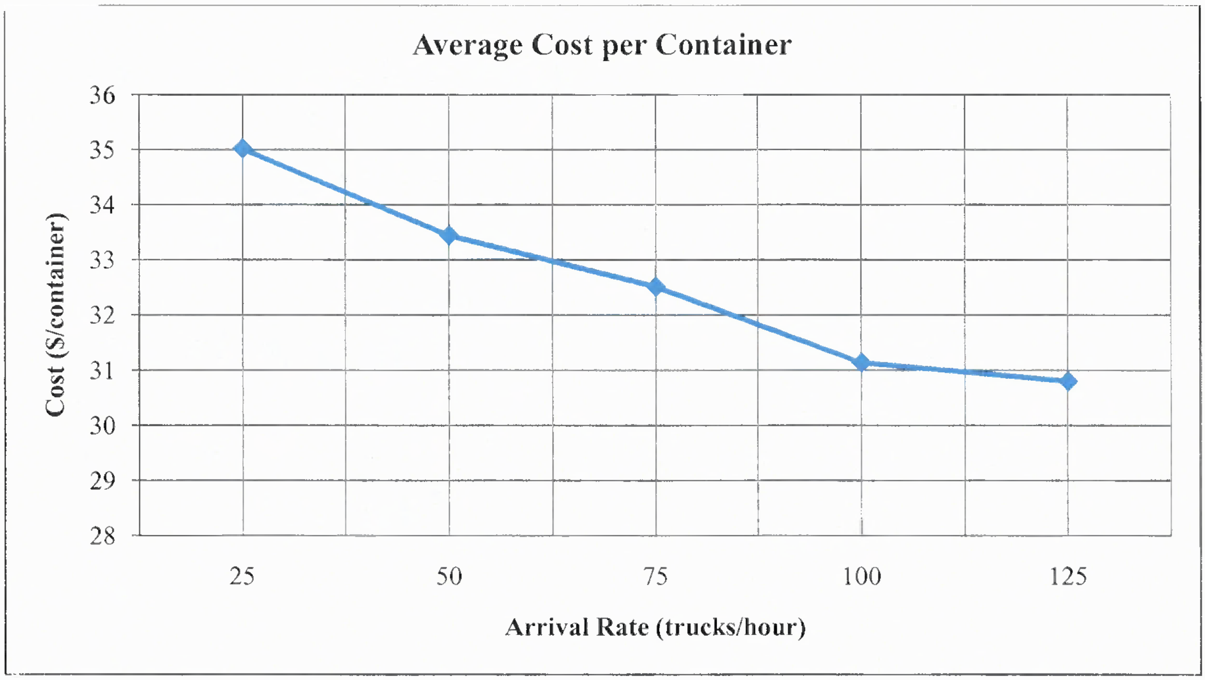

Figure 8.3 Average Cost per Container

8.6 Implications of Sampling Deviation

The solutions of the straddle carrier fleet size and planning period optimization are determined for a simulated random sample of arrival times, container locations, and truck slot locations. Each solution represents the mean of the total daily costs for a series of simulations (10 simulations in this analysis). To compare the solutions and determine the optimal solution for the problem, it is necessary to conduct a statistical analysis of results comparing the means and standard deviations of the total cost of operations for all analyzed combinations of straddle carrier fleet sizes and planning periods. Consideration of standard deviations is important as differences between means may be larger than corresponding standard deviations, making it difficult to conclude which solution is the optimal one.

As an example, for the operation with 13 straddle carriers, a planning period of 2 minutes, and an arrival rate of 125 trucks/hour, the sample mean of the total cost of operation is 38,494.37 $/day and the standard deviation is 999.05 $/day. For an operation with 12 straddle carriers, a planning period of 1 minute, and arrival rate of 125 trucks/hour, the sample mean of the total cost of operation is 38,997.45 \$/day and the standard deviation is 1,996.37 \$/day (Figure 9.3). The difference between the means is 503.08 \$/day, which is less than one standard deviation of either solution. This analysis implies that the standard deviations of the means in the simulation experiments will have to be reduced in order to make a conclusive determination of the optimal solution. This can be achieved by increasing the sample size, i.e. performing a larger number of simulations for any given truck arrival rate, straddle carrier fleet size, and planning period. Pair-wise statistical tests of the difference between the means will have to be conducted to compare the solutions for any given truck arrival rate to determine the optimal solution with a satisfactory confidence level.

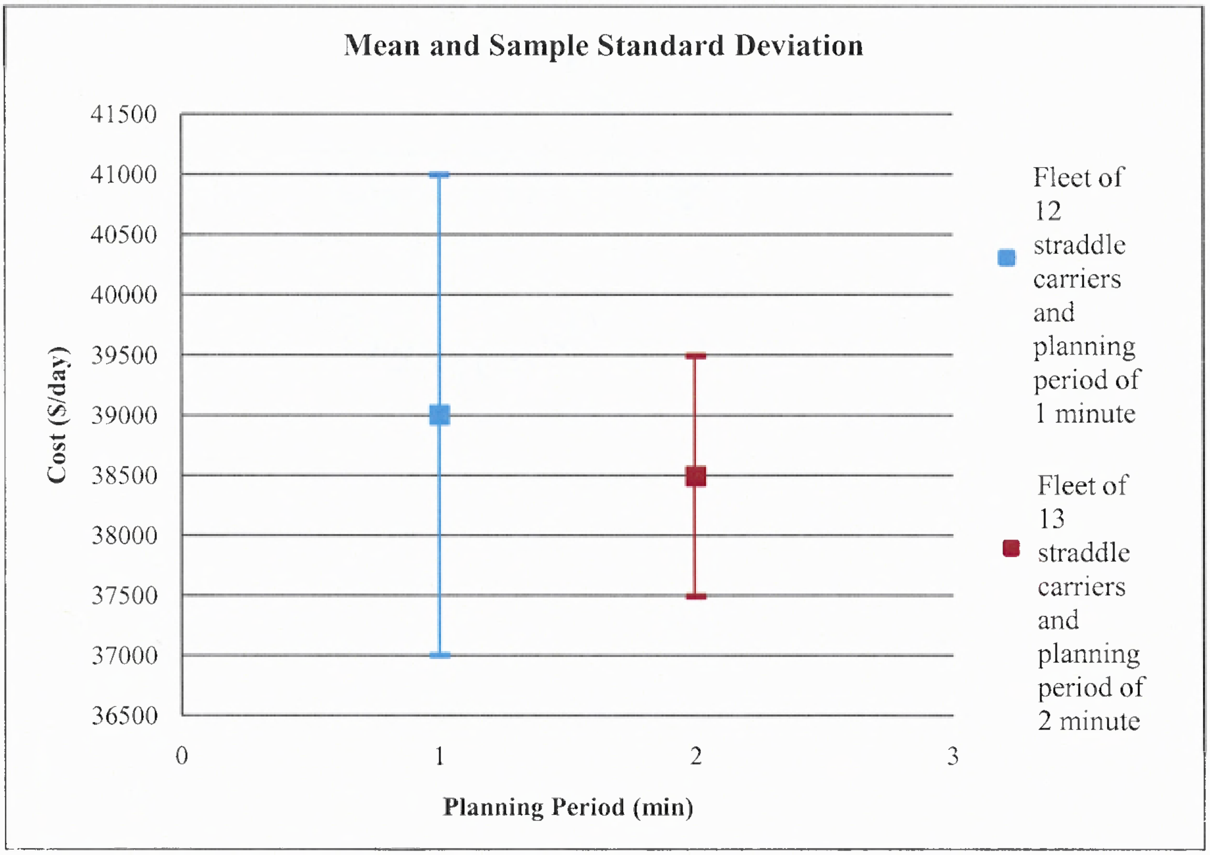

Figure 8.4 Sample means and one standard deviation range

8.7 Conclusions

The results of the experiment presented in this chapter yield the following conclusions:

- The optimal straddle carrier fleet size and the planning period depend on the truck arrival rate.
- For a specific arrival rate, the terminal operator can use the algorithms developed in this dissertation to determine the optimal straddle carrier fleet size and the optimal length of the planning period that minimize the total daily cost of operation.
- The straddle carrier fleet size and planning period that yield an optimal solution is not sensitive to the traffic imbalance(percentage of import and export containers arriving during the day)
- There seem to exist economies of scale in straddle carrier operations. A proportionate increase in the truck arrival rate results in a smaller increase in the total cost and the straddle carrier fleet size. These are likely economies of scale due to traffic density.

CHAPTER 9

MANAGEMENT IMPLICATIONS

The trade-off between the cost of operation and service quality provided to trucks is presented in this chapter. Chapter 8 found that for a given arrival rate, there is an optimal solution in terms of the straddle carrier fleet size and the planning period that yield the lowest cost of operation. The findings from Chapter 8 are used in a case study to illustrate the application of the presented model on a sample daily operation of the port terminal. The pricing structure of a truck appointment system is discussed. In this system truckers make arrangements for a premium service by scheduling in advance the arrivals at the terminal at a certain time. The operator charges a premium rate for such service.

9.1 Trade-off Between the Cost of Operation and Service Quality

The results of the experiments in Chapter 8 can be used by port terminal management to examine the impact of straddle carrier fleet size and the planning period on the cost of operation and service quality. Management can develop an equipment deployment plan that provides better service to trucks (by minimizing their waiting time) or minimizes the total cost of operation.

As an illustration, the optimal and the second best solutions are analyzed for the operation with a truck arrival rate of 50 trucks/hour. The optimal operation involves a straddle carrier fleet of 6 straddle carriers and a 4-minute planning period (Figure 9.1). The second best solution, with different fleet size, involves 5 straddle carriers and 2-minute planning period. The cost difference is $188.30 per day or approximately 1.12% of the total daily cost of operation with 6 straddle carriers. The average truck waiting time with 5 straddle carriers is 4 minute and 24 seconds, as compared to 3 minutes and 10 seconds with 6 straddle carriers, a difference of 1 minute and 14 seconds, or 28.1%. Thus, the terminal operator is incurring a marginal increase in cost by having one additional straddle carrier available.

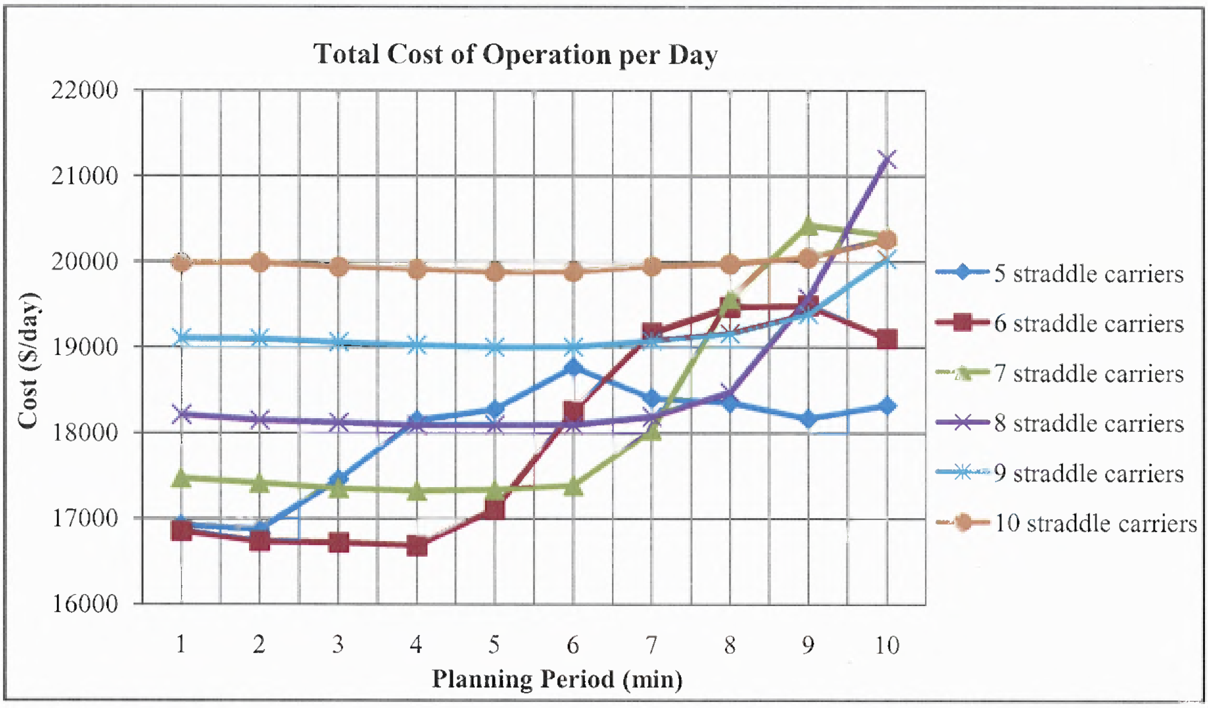

Figure 9.1 Total daily cost of operation for different straddle carrier fleet and truck arrival rate of 50 trucks/hour

Alternatively, the terminal can reduce the planning period from 4 to 2 minutes, while keeping the fleet at 6 straddle carriers. This results in a reduction of the average truck waiting time to 1 minute and 30 seconds, a 57.13% decrease (Appendix B.1 Table B.1.3). The total cost of operation increased marginally by $51.70 per day or 0.31%.

The optimal solution for a truck arrival rate of 125 trucks/hour involves 13 straddle carriers and a 2 minute planning period (shown on Figure 9.2). The reduction of the fleet to 12 straddle carriers and reduction of a planning period to 1 minute, results in reducing the average truck waiting time from 1 minute and 13 seconds to 55 seconds, while increasing the total cost by $500.08 per day. Thus, it is possible to improve service for trucks by incurring a minimal increase in cost of 1.31%.

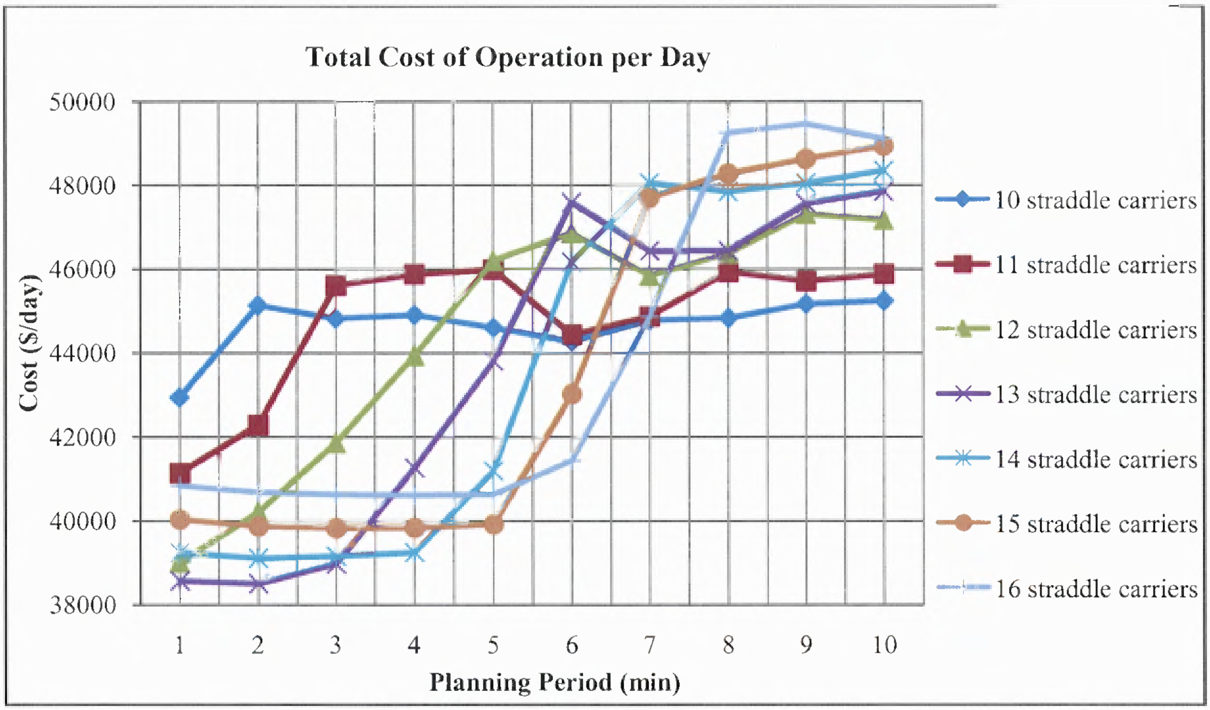

Figure 9.2 Total daily cost of operation for different straddle carrier fleet and truck arrival rate of 125 trucks/hour

The terminal operator can reduce average truck waiting time even further by reducing the planning period to one minute, while keeping the fleet size to 13 straddle carriers. The average truck waiting time is reduced to 36 seconds, and the cost of operation increased by $65.65 per day or 0.17% compared to the optimal solution.

9.2 Planning Straddle Carrier Operations with Variable Truck Arrival Rates Throughout the Day

Based on the results of the analysis presented in Chapter 8, the terminal operator can resourcefully develop an optimal operating plan that will utilize equipment more efficiently. The graph shown in Figure 9.3 represents a sample distribution of truck arrivals at the port terminal during a 10-hour work day. The entire work day can be divided into time intervals including the hours with similar truck arrival rates. For each interval (and thus the corresponding truck arrival rate), the optimal fleet of straddle carriers and the optimal planning period can be obtained using the results presented in Chapter 8.

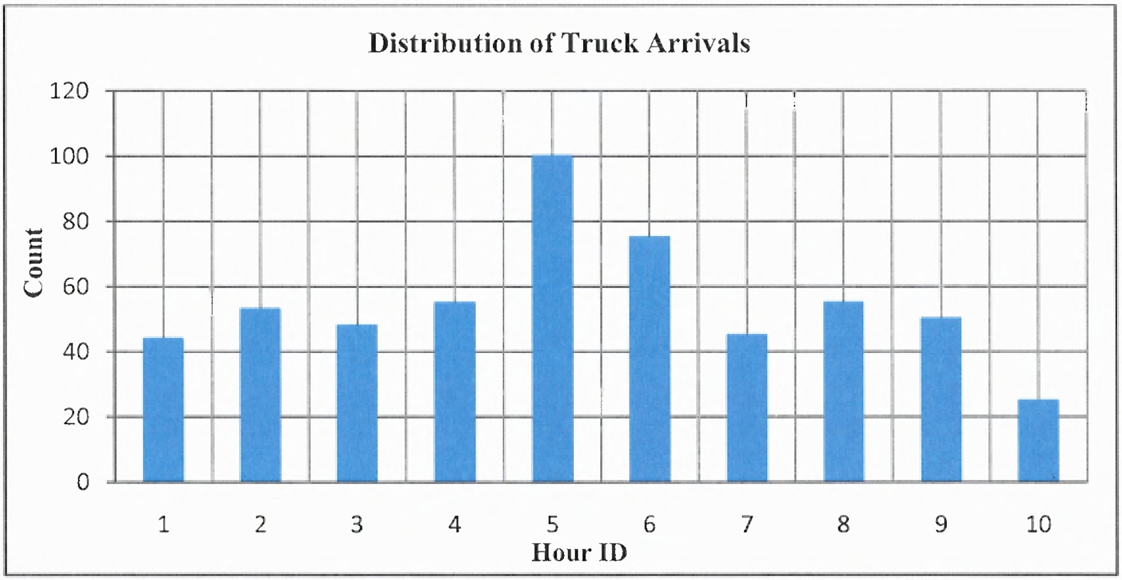

Figure 9.3 Distribution of truck arrivals in a port terminal by hour of the day

Let us first assume that the terminal operator in this case study operates a fixed straddle carrier fleet throughout the day. The optimal operating plan, yielding the minimum total daily cost of operation, involves 10 straddle carriers and a planning period of 3 minutes. The total daily cost of this operation is $16,662.58 and the average truck waiting time is 1 minute and 34 seconds. The detailed results of the analysis are shown in Table 9.1 and in Appendix A (Table A.7).

Table 9.1 Cost of Operation and Performance for 10 Straddle Carriers

Average Waiting Time Per Truck (hh:mm:ss)	00:01:34
Average Service Time per Truck (hh:mm:ss)	0:03:45
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:01:49
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:04:00
Time needed to process all jobs (hh:mm:ss)	10:15:45
Total Distance Travelled by Straddle Carriers (miles)	481.2977
Total Cost ($/day)	16,662.58

To improve the daily terminal operations, the entire work day can be divided into five different time intervals, enumerated I-V, as shown in Figure 9.4. For each interval, an average tuck arrival rate is calculated. Based on the average truck arrival rate and the analysis presented in Chapter 8, an operational plan is selected for each interval including the straddle carrier fleet size and planning period (Table 9.2).

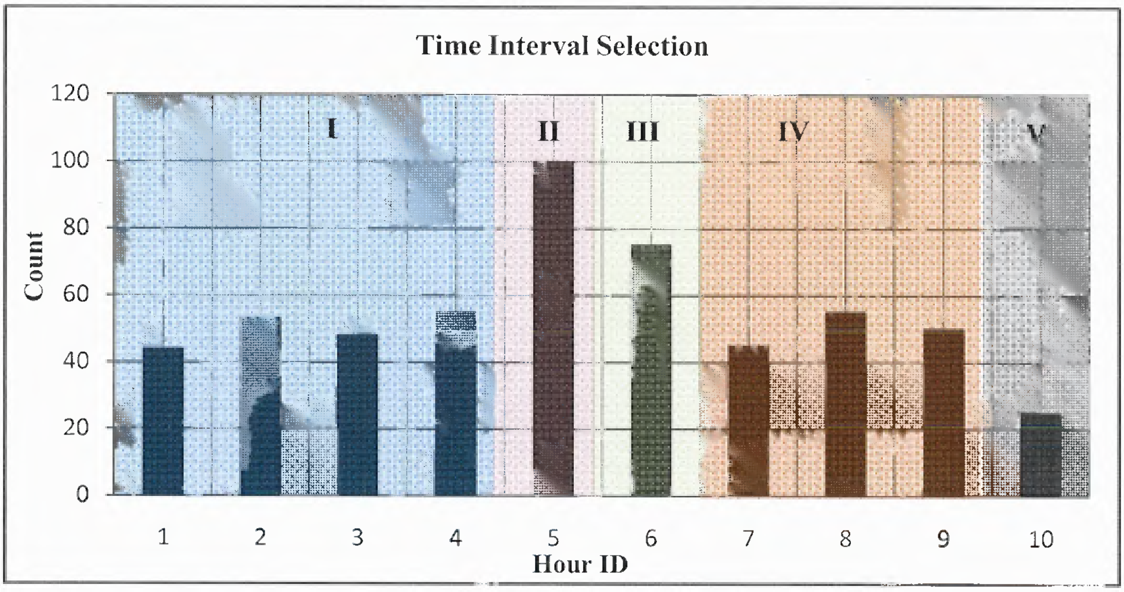

Figure 9.4 Time intervals based on similar truck arrival rates

Table 9.2 Terminal Operating Plans for Different Time Intervals During the Work Day

Operational Plan ID	**I**				**II**	**III**	**IV**			**V**
Hour ID	1	2	3	4	5	6	7	8	9	10
Actual hourly arrival rates (trucks/hr)	44	53	48	55	100	75	45	55	50	25
Average Arrival Rate (trucks/hr)	50				100	75	50			25
Straddle Carrier Fleet Size	6				10	8	6			3
Planning Period (min)	4				2	2	4			5

Time Interval I, which includes the first four operating hours, has an average truck arrival rate of 50 trucks/hour. Based on the analysis in Chapter 8, and using the optimal solution for an arrival rate of 50 trucks per hour, the optimal operational plan for this interval (Operational Plan I) involves 6 straddle carriers and a planning period of 4 minutes. In the same manner, the optimal straddle carrier fleet size and the planning period are determined for operational plans II through V (Table 9.2).

Let us first assume that the terminal operator has a fleet of 10 straddle carriers available at all times, but operates based on the operational plans presented in Table 9.2. This means that some straddle carriers will be idle in certain intervals of the day (e.g. 4 straddle carriers will be idle in Interval I, while 6 straddle carriers will be in operation). The total cost of operation in this case is 16,559.18 $/day (Table 9.3). This is a 0.6% reduction in the total daily cost of operations as compared to the previous case where all 10 straddle carriers work all day.

Table 9.3 Cost of Operation and Performance with Interval-based Operating Plans and Fixed Straddle Carrier Fleet

Average Waiting Time Per Truck (hh:mm:ss)	00:02:00
Average Service Time per Truck (hh:mm:ss)	0:04:17
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:23
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:04:32
Time needed to process all jobs (hh:mm:ss)	10:11:36
Total Distance Travelled by Straddle Carriers (miles)	478.23
Total Cost ($/day)	16,559.18

However, a terminal operator can have an operation that allows the equipment, including straddle carriers, to be shared between different yards or operating sub-systems within the terminal. In this case, the idle straddle carriers during time intervals I, III, IV, and V could be deployed to other tasks within the same terminal (e.g. ship-to-shore operations, rail yard operations, etc.). This would in effect reduce the straddle carrier ownership and associated labor cost for the analyzed yard operation, as these costs would now reside with the operation within the terminal that utilizes the equipment that would otherwise be idle. For example, the four straddle carriers that were idle during Time Interval I in the previous scenario would be deployed to the rail yard. The ownership and labor cost for these straddle carriers during Time Interval I would be charged to rail yard operations, reducing the cost of the analyzed truck operations. If this scenario is implemented in the analyzed terminal, the total cost of operations becomes 12,921.16 $/day (Table 9.4).

Table 9.4 Cost of Operation with Interval-based Operating Plans and Shared Straddle Carrier Fleet

Average Waiting Time Per Truck (hh:mm:ss)	00:02:00
Average Service Time per Truck (hh:mm:ss)	0:04:17
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:23
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:04:32
Time needed to process all jobs (hh:mm:ss)	10:11:36
Total Distance Travelled by Straddle Carriers (miles)	478.23
Total Cost ($/day)	$12,921.16

The daily cost of operation with a fixed straddle carrier fleet is $3,741.42 higher than the daily cost of operation with a shared straddle carrier fleet, a 28.96% difference. The disadvantage of this operation is that straddle carriers are limited to process only trucks, while in the operation with a shared straddle carrier fleet, straddle carriers can be deployed to different tasks within the terminal, reducing the idling, improving the equipment utilization, and ultimately reducing the equipment ownership and associated labor cost.

9.3 Pricing Structure of an Appointment System

The Ports of Los Angeles and Long Beach in California introduced a program called OffPeak in July 2003 with the objective to shift port related truck traffic from peak to off-peak hours of the day (i.e. to evening and night hours when there is less congestion on nearby highways). The idea behind the program was to extend business hours of the port terminals and institute a Peak Traffic Mitigation Fee (TMF), which would be in effect during peak hours, thus encouraging truckers (and shippers) to utilize off-peak hours to the maximum extent possible (NJIT/IITC 2008).

The knowledge of optimal straddle carrier fleet size and planning period for a given truck arrival pattern provides a good foundation for a rational pricing of truck appointments. A good pricing policy would attempt to set prices so that they cover the average or marginal cost of handling a truck-tractor and its container. Therefore, in developing a good pricing policy for appointments, the first step is to estimate the cost of handling a truck that has an appointment.

The cost of servicing a truck with an appointment will equal the marginal (or incremental) cost between the operation with appointments and the one without appointments. If appointments require a new straddle to be brought in, then the cost of this straddle must be allocated among several trucks that have appointments. If only one truck is handled, then the cost of the straddle should be fully allocated to this particular truck.

The prorated average costs of handling a truck when trucks arrive at the 25 trucks per hour rate would be $35.02 per truck[4]. If we scheduled 25 more trucks to arrive during the same hour, the additional cost would be approximately $31.87[5] per appointment. This cost is smaller compared to average cost of $ 33.45 per container for a 50 trucks/hour truck arrival rate (Chapter 8.5 Table 8.5.2).

There will be no additional cost for the operator if the appointment is made during a period when sufficient straddles are operating to serve this appointment.

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[4] This is equal the total cost of operation $8,754.79 divided by the 250 trucks served.

[5] This is equal the total cost of operation for 50 trucks per hour of $16,722.85 minus the cost of operation for 25 trucks of $8,754.79 divided by those 250 additional trucks served per day.

As to the pricing, the operator should charge the rate (price) that covers the marginal cost he will incur to service an appointment. If the marginal cost is zero, the operator will earn excess profit. To avoid charging rates that may fluctuate so as to reflect the actual marginal cost, the operator may forecast the number of appointments that will occur (or aggressively market the appointment schedule and in effect schedule them together) so that it has a certain target population of trucks that will share in the cost of a straddle. Such management of appointments will avoid a situation where a truck is charged a rate that will cover 100% of the marginal cost one day and only 10%, if the truck is one among a group of 10 appointments.

It should be pointed out that the marginal cost of an appointment got smaller when the volume increased. Due to these decreasing economies of scale, the operator stands to make excess profit. The first part of the excess profit is due to the decreasing marginal costs. The second part will come from the charging of a premium appointment rate in excess of the original average cost. For example, if the operator were to charge an appointment rate of $40 per container, then $3.15 would come from the decreased marginal cost and $4.98 would come from the difference between the appointment price and the original average cost.

9.4 Conclusion

This chapter provided an insight and offered practical guidelines on how the terminal operator can manage the straddle carrier fleet.

By removing equipment from the operation, the cost of operation increased by a small percentage. The benefit of gaining an additional straddle carrier to be employed elsewhere in the terminal is important, especially if there is a need to increase the productivity in other terminal yard areas. Reducing the planning period for the same straddle carrier fleet size leads to a smaller truck waiting time. Also, it is possible to reduce the planning period and the straddle carrier fleet size and improve service to trucks by incurring a minimal additional cost over the optimal solution (second example Chapter 9.1). The additional cost is in the 0.3 to 1.31% range.

Recognizing similar truck arrival patterns, port terminal management can develop operations based on these truck arrival patterns. Terminal management can determine optimal the straddle carrier fleet size for each truck arrival pattern and plan the operation accordingly. This enables possible deployment of excess straddle carriers to different yards.

CHAPTER 10

CONCLUSION AND THE RECOMMENDATIONS FOR FUTURE RESEARCH

This dissertation developed several new and innovative optimization models for the operational assignment of straddle carriers at the container terminal. In addition to the assignment the optimal straddle carrier fleet size is calculated. Unlike the static single period optimization where resources are optimally allocated once and only once, in real time optimization, it is critical to determine an optimal period during which the accumulation of truck requests for service would occur before the straddles are dispatched to service these requests. This dissertation makes a contribution to the field of real time transportation equipment dispatching by first introducing the concept of the planning period and then calculating it. In this chapter the results and findings are summarized and recommendations for future research are presented.

10.1 Results and Findings

A comprehensive literature review was conducted for various implementations of assignment algorithms and scheduling used to assign container handling equipment in a container terminal. The literature review did not find any attempt of delaying service to trucks for a specific period of time in order to better deploy equipment. The literature review presented guidelines for an assignment algorithm implementation and presented performance parameters that can be used to evaluate the efficiency of the operation.

Chapter 4 presented the issues that the terminal operator faces during the daily operation. The notion of optimality in real time optimization was explained and the conclusion as to the optimality of the assignment of straddle carriers to trucks were made.

The assignment models presented in Chapter 4 were used in Chapter 6 to an actual real world truck arrival pattern, obtained from the terminal operator in Port Newark, New Jersey terminal operator. The assignment in which the constant number of straddle carriers is operating throughout the whole day was analyzed. The findings are summarized below:

- The Hungarian Algorithm I provided the best solution in terms of minimizing the total distance travelled by straddles but did not consider the truck waiting time, and excessive waiting time that are not acceptable to truckers. The long wait time makes this approach unattractive to truckers and thus difficult to implement in actual operation.
- The Hungarian Algorithm II provides acceptable truck waiting times, but requires the largest straddle carrier fleet size to be employed.
- The Heuristic based on Implicit Enumeration provides an acceptable solution for the excessive waiting time of trucks. The recommendation is to deploy 6 straddle carriers and a planning period of 3 minutes. Significantly better service is provided to trucks with a minimal increase in total travel distance of 4.44%.

The impact of the truck arrival rate on straddle carrier fleet size and planning horizon was examined in Chapter 8. The results of the experiment presented yield the following conclusions:

- The optimal straddle carrier fleet size and the planning period depend on the truck arrival rate.
- For a specific arrival rate, the terminal operator can use the algorithms developed in this dissertation to determine the optimal straddle carrier fleet size and the optimal length of the planning period that minimize the total daily cost of operation.
- The straddle carrier fleet size and planning period that yield an optimal solution is not sensitive to traffic imbalance(percentage of import and export containers arriving during the day)

- There seem to exist economies of scale in straddle carrier operations. A increase in the truck arrival rate results in a smaller increase in total cost and the straddle carrier fleet size. These are likely economies of scale due to traffic density.

The trade-offs between the cost of operation and providing better service to trucks were presented in Chapter 9. The results show that port terminal management can alter the operational parameters without much sacrifice in cost. The shallowness of the cost function enables the removal of the straddle carrier from operation with a negligible cost increase (1.12%, Chapter 9.1) and reduction of the truck waiting time. Also, by changing the duration of the planning period and operating with fixed straddle carrier fleet size, the truck waiting time is reduced and the cost of operation increases by 0.17%. The managerial implication is that the straddle carrier fleet and planning period can be adjusted to meet a specific goal, and total cost will have minor deviations from the optimal solution.

The operation with variable straddle carrier fleet size and planning period was presented in Chapter 9.3. The entire work is divided into time intervals including the hours with similar truck arrival rates. For each interval (and thus the corresponding truck arrival rate), the optimal fleet of straddle carriers and the optimal planning period can be obtained using the results presented in Chapter 8. The cost of operation, compared to the cost with fixed fleet size, decreased by 28.96 % if the straddle carriers be shared between different yards or operating sub-systems within the terminal. If unused straddle carriers are idle the cost of operation is reduced by 0.6 %.

The dissertation concludes with the discussion of the pricing structure of an appointment system. The knowledge of optimal straddle carrier fleet size and planning period provides a foundation for rational pricing of truck appointments. To develop a good pricing policy for appointments, the first step is to estimate the cost of handling a truck that has an appointment.

10.2 Contributions of the Research

The methodology and findings of this dissertation would contribute in two areas (1) Assignment Algorithms Application and (2) Container Terminal Operation Management.

10.2.1 Contribution to Assignment Algorithm Application

This dissertation contributes to the application of assignment algorithms by implementing the concept of the planning period with the goal of developing an efficient allocation of straddle carriers to trucks. The research reflects an effort to implement different assignment strategies to model an important problem which arises in container terminal operations. The relationship between the planning period and straddle carrier fleet size and how they affect the operational parameters was considered in the analysis. The assignment concept can be a part of a decision support system to aid planning for container terminal operations.

10.2.2 Contribution to Port Terminal Management and Operations

The assignment concept presented in this dissertation can be a useful tool for port terminal management to evaluate different operational scenarios and can aid the decision-making process. The presented methodology and analysis provide management with tools to improve the operations. The results of the analysis presented in Chapter 8 provide decision makers insight in following areas:

- The analysis provides the optimal straddle carrier fleet size and planning period for specific truck arrival rate that will minimize the cost of operation. The total cost of operation is minimized while providing an acceptable level of service to trucks.
- The analysis evaluates the change in the total cost of operation, if the terminal operator would like to improve the service to trucks. Guidelines are presented for the port terminal operator to evaluate how the cost of operation will change, if the planning period and (or) straddle carrier fleet size is changed.
- The analysis provides insights on pricing, if an appointment system is implemented.

10.3 Recommendations for Future Research

Different objective function can be investigated in the future, and their advantages and disadvantaged can be explored. The objective function used in this research is to minimize the total distance travelled. A weighted objective function of distance travelled and truck waiting time could be implemented. Different priorities can be given to distance travelled or waiting time by varying α and β presented in equation 10.3.1

$$\text{Objective Function} = \alpha * \text{straddle distance travelled} + \beta * \text{delay in servicing trucks} \qquad (10.3.1)$$

Where:

α is a travel cost per unit distance for straddle carrier

β is a linear cost penalty for delay in servicing a truck

When trucks enter the terminal, the terminal operator knows which trucks arrived to pick-up containers, and which trucks are delivering containers. The assignment strategy that will recognize these service request and pair drop-off jobs and pick-up jobs within the planning period can be a part of future research.

Optimizing the operation between two or more yards, with shared straddle carrier fleet, can be explored as a part of future research. The optimal operational plan can be determined that provides an effective straddle carrier utilization, while ensuring satisfactory level of service to customers.

When analyzing the impact of truck arrival rates on straddle carrier fleet size and planning period, the optimization of the truck slot positions and container positions in the yard should be considered as well.

An appointment system can be implemented and its impact on the cost of operation should be determined. By redistributing the portion of trucks arriving during the peak hour to the non-peak period, a possibility to use smaller straddle carrier fleet to process service requests should be investigated. The pricing of services and incentives for truckers to make appointments should be investigated. The price of how much the terminal operator should charge for an appointment to attract truckers to utilize the off-peak hours should be investigated.

The Port Newark Container Terminal experience is that offering truckers the option to arrive during off-peak hours and have much shorter turn-around time did not attract truckers to this service. A study can be conducted, in the future, to investigate the level of service (truck service time) that will attract a higher percentage of trucks to utilize the off-peak hour service.

APPENDIX A

RESULTS OF STRADDLE CARRIERS ASSIGNMENTS

A.1 Hungarian Algorithm I - No Limits on Truck Wait Time

Table A.1 Three Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	3 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:27:31	0:41:53	0:43:49	1:08:29	1:35:32	2:09:42	2:58:53	2:59:48	3:14:09	3:26:04
Average Service Time per Truck (hh:mm:ss)	0:30:09	0:44:10	0:46:07	1:10:32	1:37:30	2:11:42	3:01:02	3:01:42	3:15:58	3:27:50
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:11:44	0:21:27	0:23:43	0:56:12	0:56:35	0:41:47	1:12:33	1:18:34	3:43:37	3:54:29
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:32:47	0:48:53	0:49:55	1:21:03	2:03:37	3:01:34	3:46:38	4:27:43	4:39:02	5:02:54
Time needed to process all jobs (hh:mm:ss)	10:32:54	10:54:28	10:57:39	11:51:06	12:43:04	13:58:29	14:55:45	15:34:27	15:45:57	15:54:41
Total Distance Travelled by Straddle Carriers (miles)	556.85	500.33	493.11	482.82	495.45	527.98	523.51	540.85	531.11	529.11

Table A.2 Four Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	4 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:05:52	0:13:04	0:21:20	0:31:20	0:59:48	1:23:20	1:49:40	2:13:01	2:29:17	2:47:34
Average Service Time per Truck (hh:mm:ss)	0:08:30	0:15:39	0:23:51	0:33:41	1:01:58	1:25:23	1:51:50	2:15:14	2:31:19	2:49:39
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:04	0:07:14	0:13:28	0:06:43	0:46:09	1:20:51	0:38:05	1:24:04	1:04:31	1:52:02
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:09:19	0:16:44	0:25:10	0:37:16	1:08:30	1:36:51	2:10:40	2:50:43	3:20:59	3:45:42
Time needed to process all jobs (hh:mm:ss)	10:13:30	10:13:30	10:13:40	10:22:54	11:08:50	11:53:35	12:28:43	13:34:09	13:39:55	13:59:14
Total Distance Travelled by Straddle Carriers (miles)	552.34	541.85	528.46	497.15	489.64	482.36	488.93	551.54	524.40	546.03

Table A.3 Five Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	5 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:01:52	0:03:49	0:06:14	0:10:27	0:30:08	0:54:47	1:17:47	1:31:36	1:47:06	2:08:17
Average Service Time per Truck (hh:mm:ss)	0:04:25	0:06:13	0:08:38	0:12:48	0:32:29	0:56:55	1:19:48	1:33:40	1:49:16	2:10:24
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:21	0:04:56	0:03:06	0:02:46	0:15:51	0:33:30	0:38:09	0:40:54	0:44:38	0:34:46
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:04:41	0:06:23	0:09:21	0:14:04	0:34:36	1:02:14	1:28:23	1:51:04	2:13:26	2:45:11
Time needed to process all jobs (hh:mm:ss)	10:13:24	10:13:24	10:13:40	10:14:38	10:12:51	10:50:38	11:23:02	11:47:52	12:15:00	12:39:05
Total Distance Travelled by Straddle Carriers (miles)	534.98	505.38	507.86	496.18	494.17	467.05	442.96	479.45	512.98	515.25

Table A.4 Six Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	6 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:00:50	0:01:44	0:03:17	0:04:57	0:12:03	0:29:52	0:51:57	1:09:05	1:22:58	1:35:56
Average Service Time per Truck (hh:mm:ss)	0:03:16	0:04:08	0:05:39	0:07:19	0:14:18	0:32:02	0:54:06	1:11:09	1:25:00	1:37:59
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:01:19	0:01:56	0:02:23	0:03:00	0:06:22	0:21:45	0:22:46	0:30:42	0:39:24	0:57:05
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:03:31	0:04:25	0:06:04	0:07:52	0:15:19	0:33:21	0:58:50	1:20:31	1:38:10	1:53:54
Time needed to process all jobs (hh:mm:ss)	10:11:40	10:12:06	10:13:40	10:14:38	10:12:06	10:14:51	10:43:31	11:09:13	11:18:59	11:37:20
Total Distance Travelled by Straddle Carriers (miles)	511.143	505.486	501.40	497.04	476.48	461.52	460.59	460.81	461.20	474.185

Table A.5 Seven Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	7 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:00:38	0:01:16	0:01:57	0:02:56	0:06:30	0:13:44	0:29:32	0:48:28	1:04:23	1:18:03
Average Service Time per Truck (hh:mm:ss)	0:03:02	0:03:38	0:04:14	0:05:15	0:08:42	0:15:55	0:31:45	0:50:36	1:06:28	1:20:02
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:01:07	0:01:30	0:02:09	0:02:51	0:04:00	0:06:19	0:09:34	0:23:43	0:19:55	0:44:19
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:03:16	0:03:55	0:04:30	0:05:33	0:09:18	0:17:09	0:34:35	0:54:57	1:15:26	1:30:03
Time needed to process all jobs (hh:mm:ss)	10:11:40	10:12:06	10:13:40	10:14:32	10:12:06	10:14:09	10:17:40	10:36:17	10:54:28	11:04:31
Total Distance Travelled by Straddle Carriers (miles)	503.09	500.84	483.25	488.56	466.17	463.58	467.94	460.19	458.20	447.26

Table A.6 Eight Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	8 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:00:35	0:01:06	0:01:39	0:02:19	0:03:29	0:08:30	0:14:30	0:29:22	0:46:42	1:02:20
Average Service Time per Truck (hh:mm:ss)	0:02:55	0:03:25	0:03:55	0:04:37	0:05:47	0:10:39	0:16:40	0:31:34	0:48:52	1:04:24
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:01:00	0:01:25	0:01:58	0:02:36	0:03:16	0:03:58	0:07:35	0:09:44	0:08:54	0:25:24
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:03:09	0:03:40	0:04:10	0:04:52	0:06:06	0:11:30	0:17:49	0:34:21	0:54:37	1:11:43
Time needed to process all jobs (hh:mm:ss)	10:11:40	10:12:16	10:13:40	10:14:25	10:12:06	10:14:09	10:17:40	10:18:51	10:30:40	10:41:31
Total Distance Travelled by Straddle Carriers (miles)	490.351	489.228	476.662	484.975	486.162	457.597	460.447	467.594	463.470	453.15

Table A.7 Ten Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	10 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Waiting Time Per Truck	0:00:35	0:01:04	0:01:34	0:02:07	0:02:39	0:03:34	0:06:39	0:11:10	0:16:44	0:32:30
Average Service Time per Truck (hh:mm:ss)	0:02:49	0:03:18	0:03:45	0:04:20	0:04:51	0:05:46	0:08:48	0:13:20	0:18:53	0:34:38
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:00:52	0:01:16	0:01:49	0:02:27	0:03:00	0:03:13	0:04:43	0:06:50	0:08:57	0:18:37
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:03:04	0:03:34	0:04:00	0:04:34	0:05:05	0:06:06	0:09:19	0:14:09	0:20:09	0:36:40
Time needed to process all jobs (hh:mm:ss)	10:11:40	10:12:22	10:15:45	10:16:25	10:17:06	10:17:09	10:17:40	10:18:25	10:17:25	10:18:06
Total Distance Travelled by Straddle Carriers (miles)	486.40	482.13	481.29	487.37	488.471	487.529	496.863	491.476	484.575	481.854

A.2 Hungarian Algorithm II - With Truck Priority

Table A.8 Three Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	3 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	1:26:35	0:50:17	0:42:38	0:28:29	0:29:41	0:26:28	0:25:55
Average Service Time per Truck (hh:mm:ss)	1:29:14	0:52:44	0:45:06	0:30:54	0:32:09	0:28:54	0:28:23
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:43:56	0:04:00	0:10:23	0:06:45	0:08:47	0:12:00	0:14:13
Average Service Time for Pick-Up Truck (hh:mm:ss)	1:35:25	0:59:11	0:49:44	0:34:03	0:35:16	0:31:12	0:30:19
Time needed to process all jobs (hh:mm:ss)	12:58:21	11:29:24	11:21:44	10:46:20	10:44:39	10:32:30	10:34:43
Total Distance Travelled by Straddle Carriers (miles)	556.48	519.09	521.01	510.02	519.69	517.34	520.23

Table A.9 Four Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	4 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:38:25	0:21:48	0:13:51	0:08:51	0:10:20	0:10:23	0:09:50
Average Service Time per Truck (hh:mm:ss)	0:40:52	0:24:14	0:16:18	0:11:11	0:12:44	0:12:44	0:12:10
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:53	0:04:00	0:03:53	0:05:30	0:06:11	0:05:51	0:06:45
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:45:54	0:26:56	0:17:53	0:11:55	0:13:35	0:13:36	0:12:51
Time needed to process all jobs (hh:mm:ss)	11:02:02	10:23:23	10:14:51	10:17:40	10:18:45	10:14:38	10:12:06
Total Distance Travelled by Straddle Carriers (miles)	517.62	514.38	518.42	492.58	506.72	496.38	493.42

Table A.10 Five Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	5 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:23:54	0:08:27	0:05:45	0:06:11	0:06:47	0:06:40	0:07:58
Average Service Time per Truck (hh:mm:ss)	0:26:19	0:10:49	0:08:10	0:08:33	0:09:12	0:09:00	0:10:20
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:41	0:03:41	0:04:40	0:04:22	0:05:00	0:05:30	0:06:37
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:29:27	0:11:44	0:08:37	0:09:06	0:09:44	0:09:27	0:10:48
Time needed to process all jobs (hh:mm:ss)	10:49:08	10:13:04	10:14:06	10:17:40	10:18:06	10:14:38	10:12:06
Total Distance Travelled by Straddle Carriers (miles)	510.86	498.62	508.10	499.87	508.64	491.13	498.02

Table A.11 Six Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	6 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:21:31	0:04:49	0:04:36	0:04:25	0:05:12	0:05:34	0:06:21
Average Service Time per Truck (hh:mm:ss)	0:23:55	0:07:09	0:06:56	0:06:42	0:07:33	0:07:52	0:08:39
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:39	0:04:10	0:03:52	0:04:17	0:04:42	0:05:25	0:06:24
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:26:45	0:07:31	0:07:19	0:07:01	0:07:55	0:08:10	0:08:56
Time needed to process all jobs (hours)	10:46:45	10:13:04	10:14:32	10:17:40	10:18:32	10:14:06	10:12:06
Total Distance Travelled by Straddle Carriers (miles)	508.53	491.37	492.66	482.34	494.26	483.79	485.49

Table A.12 Seven Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	7 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:21:21	0:03:43	0:03:49	0:04:09	0:04:47	0:05:08	0:06:05
Average Service Time per Truck (hh:mm:ss)	0:23:45	0:05:58	0:06:06	0:06:26	0:07:05	0:07:22	0:08:22
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:32	0:03:23	0:03:08	0:04:02	0:04:34	0:05:08	0:06:07
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:26:34	0:06:18	0:06:29	0:06:45	0:07:24	0:07:39	0:08:39
Time needed to process all jobs (hh:mm:ss)	10:39:02	10:12:06	10:14:09	10:17:40	10:18:32	10:14:06	10:12:06
Total Distance Travelled by Straddle Carriers (miles)	508.47	478.02	481.20	482.43	485.43	473.08	483.23

Table A.13 Eight Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	8 Straddle Carriers in Operation						
	Planning Period (min)						
	4	5	6	7	8	9	10
Average Waiting Time Per Truck (hh:mm:ss)	0:18:03	0:03:10	0:03:37	0:04:00	0:04:33	0:05:01	0:05:53
Average Service Time per Truck (hh:mm:ss)	0:20:24	0:05:25	0:05:51	0:06:14	0:06:50	0:07:15	0:08:09
Average Service Time per Drop-Off Truck (hh:mm:ss)	0:02:31	0:03:07	0:03:14	0:03:56	0:04:22	0:05:06	0:06:03
Average Service Time for Pick-Up Truck (hh:mm:ss)	0:22:47	0:05:42	0:06:11	0:06:31	0:07:09	0:07:31	0:08:25
Time needed to process all jobs (hh:mm:ss)	10:31:12	10:12:06	10:14:09	10:17:40	10:18:25	10:14:25	10:12:06
Total Distance Travelled by Straddle Carriers (miles)	499.33	474.72	473.21	473.70	482.86	471.83	478.41

A.3 Heuristic with Implicit Enumeration

Table A.14 Four Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	4 Straddle Carriers in Operation							
	Planning Period (min)							
	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:41:54	0:37:52	0:31:53	0:21:44	0:24:31	0:36:11	0:28:49	0:45:26
Average service time per truck (hh:mm:ss)	0:44:06	0:40:05	0:34:08	0:23:57	0:26:42	0:38:25	0:31:02	0:47:38
Average service time for drop-off truck (hh:mm:ss)	0:33:12	0:42:14	0:35:43	0:23:32	0:26:00	0:39:02	0:32:49	0:51:27
Average service time for pick-up truck (hh:mm:ss)	0:45:30	0:39:48	0:33:56	0:24:00	0:26:47	0:38:21	0:30:48	0:47:08
Time Needed To finish all jobs (hh:mm:ss)	10:46:58	10:14:51	10:12:51	10:14:51	10:17:40	10:27:46	10:14:25	11:03:19
Total Distance Traveled by Straddle Carriers (miles)	466.88	465.93	475.54	468.16	462.74	471.96	466.88	465.00

Table A.15 Five Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	5 Straddle Carriers in Operation							
	Planning Period (min)							
	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:21:02	0:20:51	0:30:55	0:24:37	0:31:16	0:21:22	0:24:52	0:26:27
Average service time per truck (hh:mm:ss)	0:23:14	0:23:01	0:33:09	0:26:48	0:33:29	0:23:33	0:27:05	0:28:38
Average service time for drop-off truck (hh:mm:ss)	0:20:59	0:20:36	0:35:56	0:24:30	0:32:24	0:20:33	0:29:28	0:25:08
Average service time for pick-up truck (hh:mm:ss)	0:23:31	0:23:20	0:32:47	0:27:05	0:33:37	0:23:56	0:26:47	0:29:05
Time Needed To finish all jobs (hh:mm:ss)	10:13:40	10:14:25	10:12:51	10:14:51	10:17:40	10:18:51	10:14:51	10:12:51
Total Distance Traveled by Straddle Carriers (miles)	464.23	459.15	469.11	460.64	469.32	463.77	467.72	462.41

Table A.16 Six Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	6 Straddle Carriers in Operation							
	Planning Period (min)							
	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:13:43	0:20:33	0:32:21	0:13:56	0:20:48	0:23:06	0:19:40	0:22:19
Average service time per truck (hh:mm:ss)	0:15:51	0:22:43	0:34:35	0:16:05	0:22:58	0:25:16	0:21:51	0:24:32
Average service time for drop-off truck (hh:mm:ss)	0:12:56	0:15:51	0:38:24	0:15:45	0:24:29	0:23:39	0:22:30	0:22:48
Average service time for pick-up truck (hh:mm:ss)	0:16:13	0:23:36	0:34:06	0:16:08	0:22:46	0:25:29	0:21:46	0:24:45
Time Needed To finish all jobs (hh:mm:ss)	10:13:40	10:14:51	10:12:51	10:14:51	10:17:40	10:18:51	10:14:51	10:12:51
Total Distance Traveled by Straddle Carriers (hh:mm:ss)	450.88	456.13	469.93	455.09	462.28	459.33	459.67	464.38

Table A.17 Seven Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	7 Straddle Carriers in Operation							
	Planning Period (min)							
	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:12:37	0:16:10	0:16:59	0:15:47	0:17:03	0:19:34	0:21:02	0:26:29
Average service time per truck (hh:mm:ss)	0:14:45	0:18:18	0:19:10	0:17:55	0:19:11	0:21:44	0:23:15	0:28:42
Average service time for drop-off truck (hh:mm:ss)	0:12:34	0:15:51	0:17:26	0:15:45	0:19:23	0:20:23	0:24:29	0:26:34
Average service time for pick-up truck (hh:mm:ss)	0:15:02	0:18:37	0:19:24	0:18:12	0:19:09	0:21:51	0:23:06	0:28:59
Time Needed To finish all jobs (hh:mm:ss)	10:13:40	10:14:51	10:12:51	10:14:25	10:17:40	10:18:51	10:14:51	10:12:51
Total Distance Traveled by Straddle Carriers (miles)	455.29	451.81	463.13	454.14	454.73	459.35	467.70	468.35

Table A.18 Eight Straddle Carriers in Operation with a Planning Horizon of Varying Duration

	8 Straddle Carriers in Operation							
	Planning Period (min)							
	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:13:33	0:11:06	0:16:36	0:13:32	0:20:07	0:16:59	0:20:20	0:23:34
Average service time per truck (hh:mm:ss)	0:15:42	0:13:15	0:18:46	0:15:40	0:22:16	0:19:07	0:22:31	0:25:45
Average service time for drop-off truck (hh:mm:ss)	0:14:15	0:12:35	0:15:52	0:14:45	0:20:48	0:16:52	0:23:16	0:24:09
Average service time for pick-up truck (hh:mm:ss)	0:15:53	0:13:21	0:19:08	0:15:47	0:22:27	0:19:24	0:22:26	0:25:57
Time Needed To finish all jobs (hh:mm:ss)	10:13:40	10:14:51	10:12:51	10:14:25	10:17:40	10:18:51	10:14:51	10:12:25
Total Distance Traveled by Straddle Carriers (miles)	454.75	455.37	458.44	452.68	454.88	451.77	463.28	459.52

APPENDIX B

RESULTS OF THE EXPERIMENT

B.1 Optimal Solution for Different Arrival Rates

Table B.1.1 Three Straddle Carriers in Operation For Truck Arrival Rate of 25 trucks/hour

	3 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	0:01:14	0:02:11	0:03:17	0:04:44	0:06:03	0:12:28	0:22:03	0:41:26	1:09:22	1:39:37
Average service time per truck (hh:mm:ss)	0:05:03	0:06:01	0:07:05	0:08:32	0:09:47	0:16:09	0:25:13	0:41:31	1:03:36	1:23:05
Average service time for drop-off truck (hh:mm:ss)	0:02:12	0:02:54	0:03:44	0:04:16	0:04:57	0:06:31	0:09:56	0:10:02	0:21:57	0:34:10
Average service time for pick-up truck (hh:mm:ss)	0:05:24	0:06:24	0:07:30	0:09:04	0:10:25	0:17:43	0:28:05	0:49:47	1:19:41	1:52:02
Time Needed To finish all jobs (hh:mm:ss)	10:00:11	10:01:46	10:02:15	10:03:47	10:04:07	10:20:08	10:37:57	11:13:19	11:58:15	12:38:09
Overtime(hh:mm:ss)	00:00:11	00:01:46	00:02:15	00:03:47	00:04:07	00:20:08	00:37:57	1:13:19	1:58:15	2:38:09
Total Distance Traveled by Straddle Carriers (miles)	391.86	392.52	389.002	391.835	386.56	413.115	417.32	424.838	425.9754	418.925
Total Operating Cost ($/day)	7296.10	7312.22	7264.35	7310.92	7237.79	7684.12	7820.77	8080.69	8291.25	8363.81
Total Ownership Cost ($/day)	1517.01									
Total Cost ($/day)	8813.10	8829.23	8781.35	8827.93	8754.79	9201.13	9337.78	9597.70	9808.26	9880.81

Table B.1.2 Six Straddle Carriers in Operation For Truck Arrival Rate of 50 trucks/hour

	6 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	00:00:48	00:01:30	00:02:22	00:03:10	00:05:21	00:11:08	00:25:48	00:50:41	01:26:57	01:59:09
Average service time per truck (hh:mm:ss)	00:04:22	00:05:02	00:05:53	00:06:40	00:08:56	00:14:47	00:29:00	00:48:40	01:19:33	01:29:39
Average service time for drop-off truck (hh:mm:ss)	00:01:28	00:02:02	00:02:33	00:03:16	00:04:01	00:05:38	00:08:29	00:14:10	00:27:23	00:59:00
Average service time for pick-up truck (hh:mm:ss)	00:04:42	00:05:22	00:06:16	00:07:04	00:09:33	00:16:11	00:32:25	00:59:30	01:38:10	02:09:53
Time Needed To finish all jobs (hh:mm:ss)	10:03:43	10:04:21	10:06:54	10:07:31	10:12:48	10:30:30	11:03:10	11:45:01	12:34:45	13:06:26
Overtime (hh:mm:ss)	00:03:43	10:04:21	00:06:54	00:07:31	00:12:48	00:30:30	01:03:10	01:45:01	02:34:45	03:06:26
Total Distance Traveled by Straddle Carriers (miles)	779.12	770.48	767.79	764.90	791.58	861.70	905.91	901.75	872.58	826.20
Total Operating Cost ($/day)	15012.42	14959.72	15539.73	16231.71	16358.97	16851.08	16487.68	16437.678	16250.38	16406.63
Total Ownership Cost ($/day)	2299.05									
Total Cost ($/day)	16856.23	16738.99	16722.85	16687.30	17111.82	18260.78	19171.10	19474.28	19490.43	19105.99

Table B.1.3 Eight Straddle Carriers in Operation For Truck Arrival Rate of 75 trucks/hour

	8 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	00:00:48	00:02:11	00:03:55	00:06:58	00:10:29	00:30:03	00:47:36	01:19:21	01:58:27	02:29:50
Average service time per truck (hh:mm:ss)	00:04:24	00:05:50	00:07:31	00:10:40	00:14:03	00:31:53	00:47:41	01:06:33	01:37:54	01:37:55
Average service time for drop-off truck (hh:mm:ss)	00:01:25	00:02:09	00:02:36	00:03:32	00:04:13	00:06:09	00:07:34	00:20:04	00:35:13	00:56:45
Average service time for pick-up truck (hh:mm:ss)	00:04:25	00:04:59	00:05:35	00:06:30	00:08:05	00:13:02	00:29:55	00:52:10	01:30:11	02:04:16
Time Needed To finish all jobs (hh:mm:ss)	10:05:18	10:09:21	10:14:13	10:25:34	10:40:56	11:25:04	11:56:09	12:42:15	13:33:44	14:03:29
Overtime (hh:mm:ss)	00:05:18	00:09:21	00:14:13	00:25:34	00:40:56	00:25:04	01:56:09	02:42:15	03:33:44	04:03:29
Total Distance Traveled by Straddle Carriers (miles)	1173.63	1168.53	1166.42	1228.27	1282.34	1382.67	1381.52	1300.06	1301.97	1256.15
Total Operating Cost ($/day)	21341.97	21316.25	21342.706	22351.74	23296.88	25230.87	25573.23	24948.26	25569.57	25262.12
Total Ownership Cost ($/day)	3065.4									
Total Cost ($/day)	24407.38	24381.66	24408.11	25417.15	26362.28	28296.27	28638.68	28013.67	28634.98	28327.52

Table B.1.4 Ten Straddle Carriers in Operation For Truck Arrival Rate of 100 trucks/hour

	10 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	00:00:45	00:01:47	00:06:12	00:15:34	00:26:57	00:46:45	01:04:20	01:43:35	02:22:13	02:52:24
Average service time per truck (hh:mm:ss)	00:04:15	00:05:20	00:09:59	00:19:08	00:29:21	00:45:35	01:01:20	01:21:22	01:51:45	01:46:07
Average service time for drop-off truck (hh:mm:ss)	00:01:25	00:02:01	00:02:57	00:04:18	00:05:16	00:07:02	00:10:45	00:20:24	00:37:33	01:04:37
Average service time for pick-up truck (hh:mm:ss)	00:04:33	00:05:43	00:10:50	00:21:26	00:34:04	00:56:00	01:15:01	01:57:18	02:38:02	03:08:23
Time Needed To finish all jobs (hh:mm:ss)	10:04:14	10:05:12	10:21:20	10:51:09	11:18:40	11:58:55	12:29:12	13:29:54	14:16:17	14:41:29
Overtime (hh:mm:ss)	00:04:14	00:05:12	00:21:20	00:51:09	01:18:40	01:58:55	02:29:12	03:29:54	04:16:17	04:41:29
Total Distance Traveled by Straddle Carriers (miles)	1515.93	1511.01	1630.75	1753.21	1791.03	1853.75	1826.67	1748	1662.65	1593.28
Total Operating Cost ($/day)	27359.67	27300.42	29233.60	31402.60	32336.46	33807.79	33859.870	33618.261	33075.245	32453.574
Total Ownership Cost ($/day)	3831.75									
Total Cost ($/day)	31191.42	31132.17	33065.36	35234.36	36168.22	37639.54	37691.62	37450.02	36907.00	36285.33

Table B.1.5 Thirteen Straddle Carriers in Operation For Truck Arrival Rate of 125 trucks/hour

	13 Straddle Carriers in Operation									
	Planning Period (min)									
	1	2	3	4	5	6	7	8	9	10
Average Truck Waiting Time for service (hh:mm:ss)	00:00:36	00:01:13	00:02:10	00:07:16	00:15:25	00:36:49	00:51:54	01:26:11	02:06:15	02:39:20
Average service time per truck (hh:mm:ss)	00:04:01	00:04:38	00:05:37	00:10:45	00:18:31	00:37:23	00:50:55	01:10:57	01:42:49	01:42:49
Average service time for drop-off truck (hh:mm:ss)	00:01:12	00:01:40	00:02:21	00:03:08	00:04:11	00:06:39	00:12:39	00:16:26	00:27:40	00:44:36
Average service time for pick-up truck (hh:mm:ss)	00:04:19	00:04:57	00:05:59	00:11:50	00:21:06	00:44:59	01:00:48	01:38:15	02:21:27	02:56:11
Time Needed To finish all jobs (hh:mm:ss)	10:04:38	10:05:47	10:08:54	10:31:15	10:58:34	11:48:07	12:09:22	13:04:25	13:59:03	14:34:50
Overtime (hh:mm:ss)	00:04:38	00:05:47	00:08:54	00:31:15	00:58:34	01:48:07	02:09:22	03:04:25	03:59:03	04:34:50
Total Distance Traveled by Straddle Carriers (miles)	1830.28	1824.26	1853.10	1985.22	2128.60	2329.94	2220.34	2148.11	2154.85	2128.15
Total Operating Cost ($/day)	33578.74	33513.09	33980.93	36276.01	38824.19	42612.43	41454.58	41461.01	42581.11	42872.92
Total Ownership Cost ($/day)	4981.27									
Total Cost ($/day)	38560.02	38494.37	38962.21	41257.29	43805.47	47593.71	46435.86	46442.29	47562.39	47854.20

B.2 Simulation Results for Truck Arrival Rates Ranging from 25 Truck per Hour to 125 Trucks per Hour

B.2.1 Results for Truck Arrival Rate of 25 trucks per hour

The total cost of operation per day, shown in Figure B.2.1, is an average cost obtained from ten simulation runs. For example, the $ 8754.79 cost of operating for a fleet size of 5 straddle carriers dispatched every five minutes is the average cost of ten simulations.

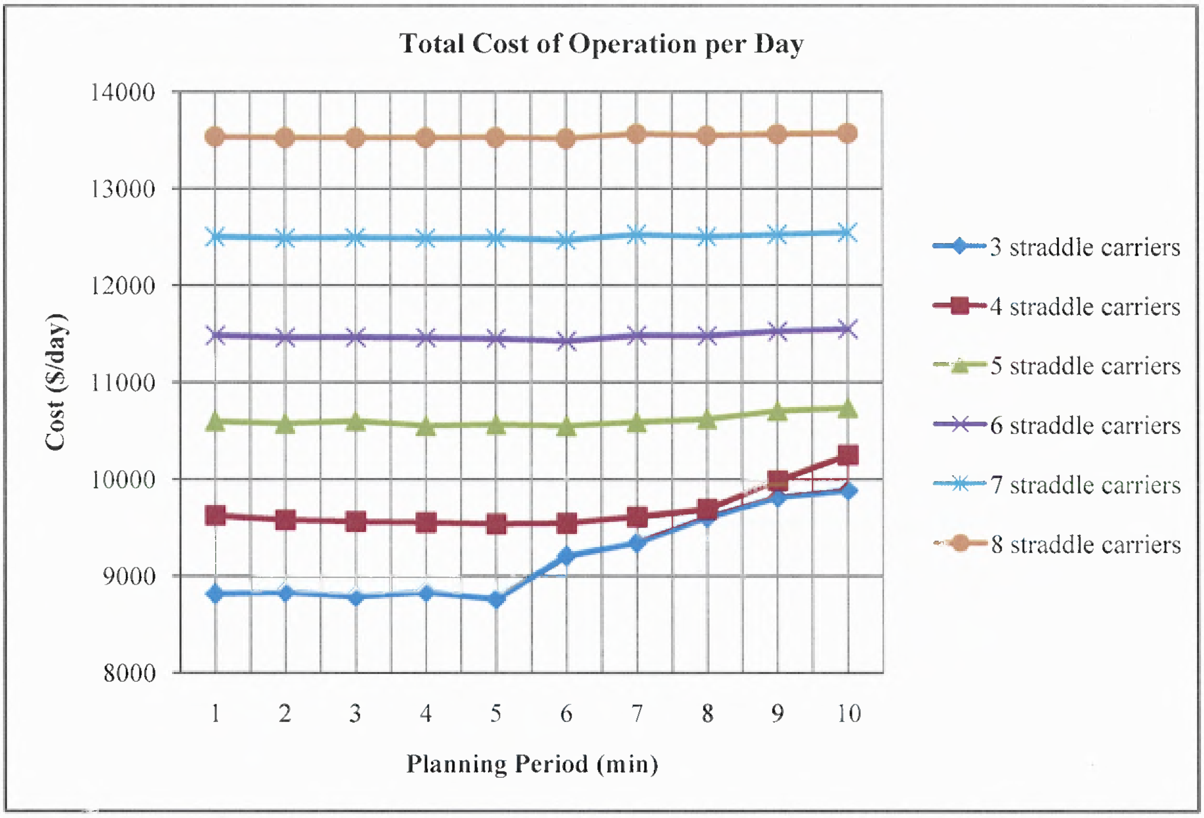

Figure B.2.1 Total cost of operation per day for arrival rate of 25 trucks per hour

Figure B.2.1 shows that the optimal operation in terms of minimizing the daily cost of operation is obtained with three straddle carriers and with the assignment decision being made every five minutes. As the duration of the planning period increases from 1 to 10 minutes the cost of operation with 3 straddle carriers starts to increase after the planning period has increased beyond 5 minutes.

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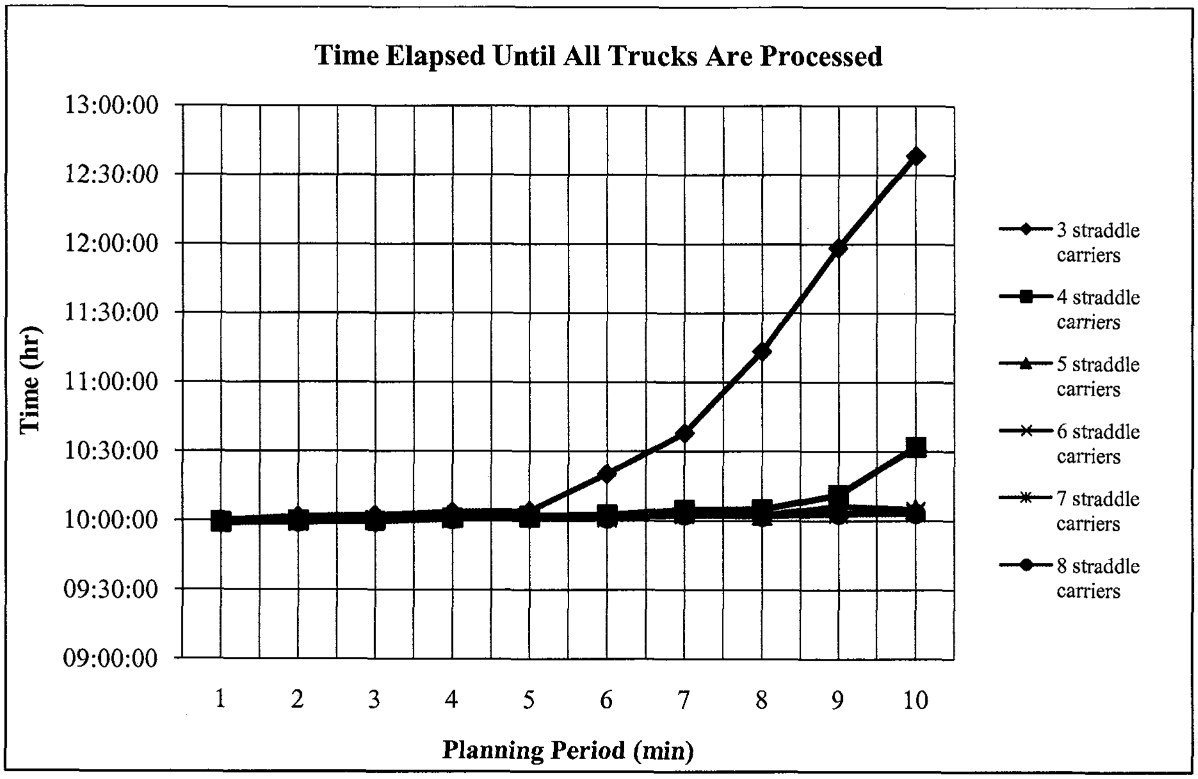

Figure B.2.3 Time elapsed until all trucks are processed for arrival rate of 25 trucks per hour

B.2.2 Simulation Results Based on Truck Arrival Rate of 50 trucks per hour

Figure B.2.4 shows that increasing the average truck arrival rate to 50 trucks per hour resulted in an optimal assignment scenario of having 6 straddle carriers in operation with dispatching decision being made every four minutes. The increase in the arrival rate resulted in adding 3 additional straddle carriers to accommodate requests for service and resulted in reducing the duration of the planning period, so that the assignment can be evaluated more frequently. The operation with 6 straddle carriers requires additional 7 minutes and 31 seconds in overtime in order to process all trucks arrived during the regular operating hours (Appendix B Table B.1.2).

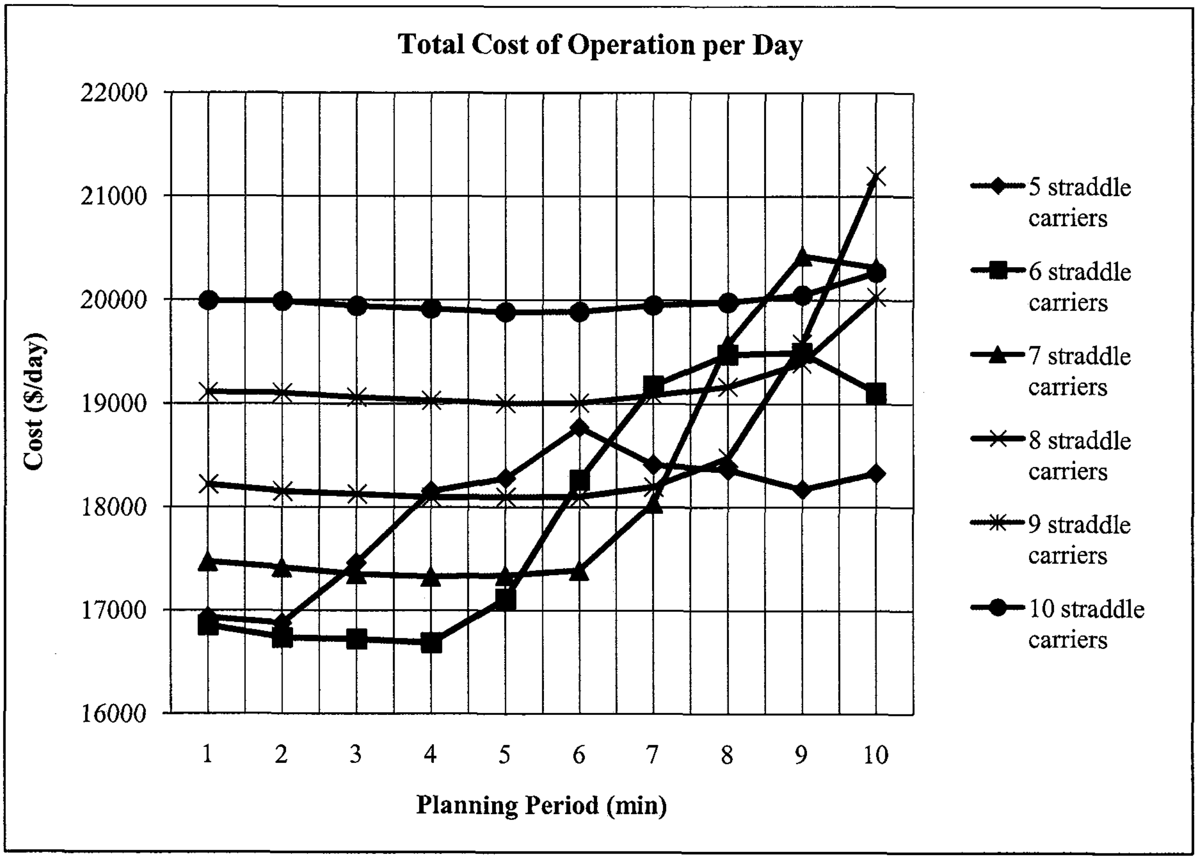

Figure B.2.4 Total cost of operation per day for arrival rate of 50 trucks per hour

As the duration of the planning period increases, for example, for the operation with 6 straddle carriers and the planning period duration beyond 4 minutes, or operation with 7 straddle carriers and the planning period duration beyond 6 minutes, the cost of operation increases. The total distance travelled by straddle carriers increased significantly and thus resulting in cost increase. Also the overtime required to process remaining trucks increased, resulting in 50% additional cost for straddle carrier operators wages (Figure B.2.5).

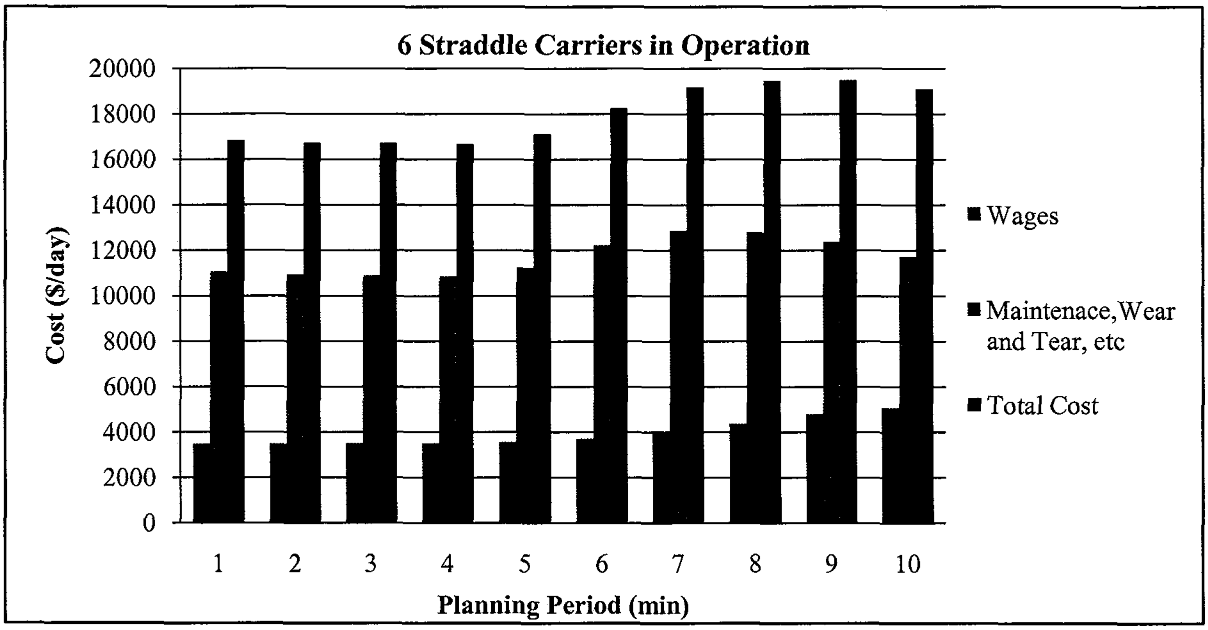

Figure B.2.5 Change in cost for the operation with fleet size of 6 straddle carriers

The average truck waiting time for service is 3 minutes and 10 seconds. This is an acceptable waiting time for truckers (Appendix B Table B.1.2). Also, from Figure B.2.6, it can be observed that the average truck waiting time has an increasing trend as the planning period duration increases.

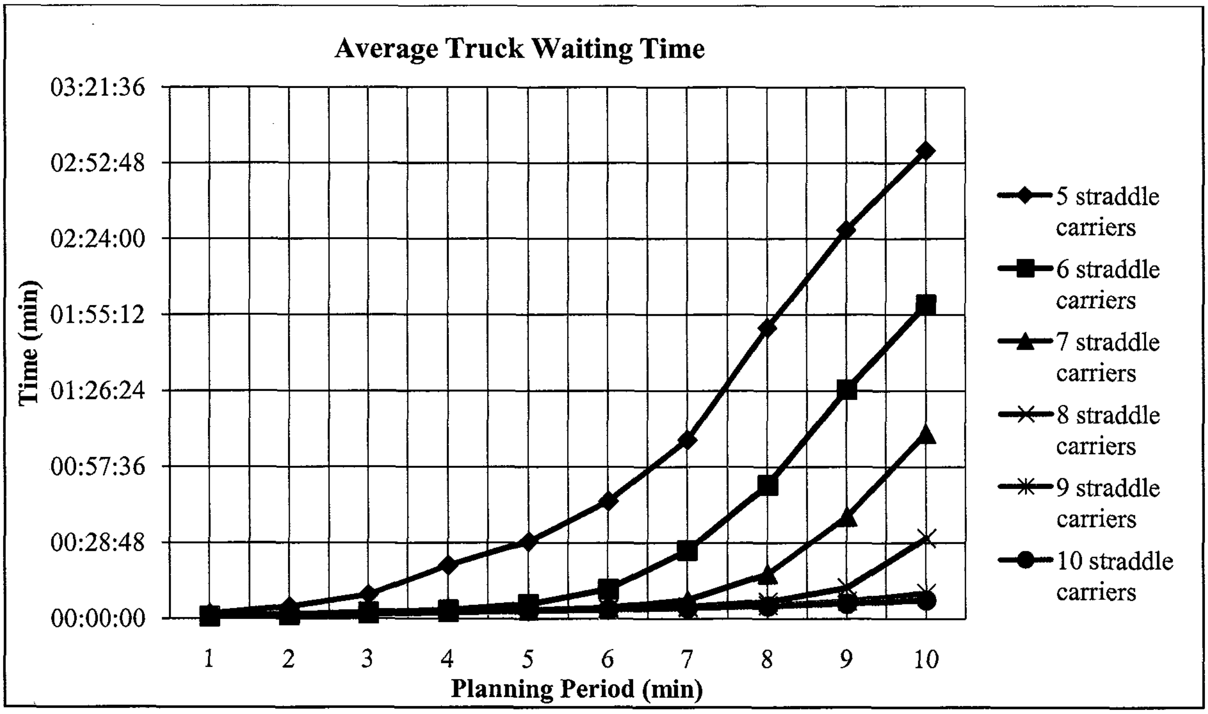

Figure B.2.6 Average truck waiting time for service for arrival rate of 50 trucks per hour

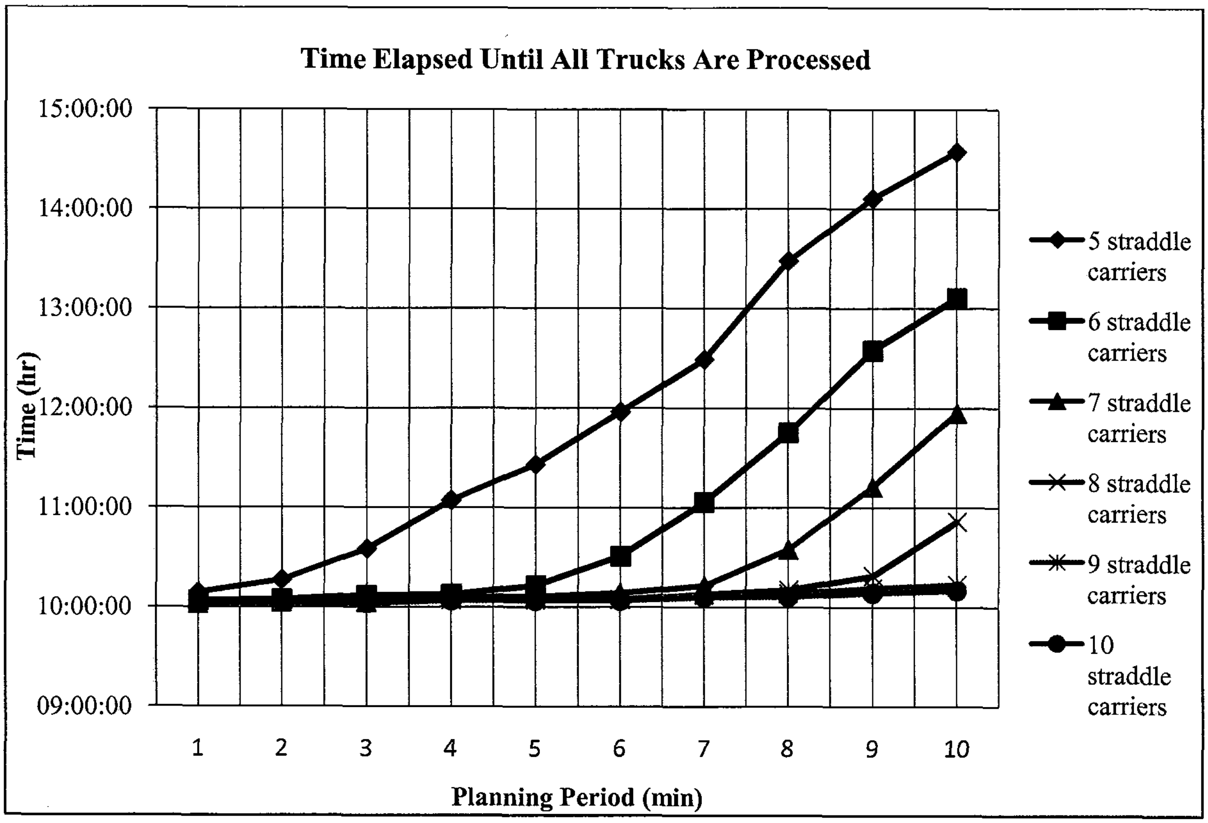

Figure B.2.7 Time elapsed until all trucks are processed for arrival rate of 50 trucks per hour

Figure B.2.7 shows the change in total time required to process all trucks. For the straddle carrier fleet size with less than 9 straddle carriers, the change in total time elapsed to process trucks has an increasing trend as the planning period increases.

B.2.3 Simulation Results Based on Truck Arrival Rate of 75 trucks per hour

For the truck arrival rate of 75 trucks per hour the candidate number of straddle carriers in operation was in the range from 6 to 12. The lowest daily cost of operation is achieved with 8 straddle carriers and with the planning period of 2 minutes (Figure B.2.8). The pattern observed in the case of 25 and 50 truck per hour arrival rate remains. An increase in the arrival rate requires adding of additional straddle carriers which are now being dispatched in a shorter planning period.

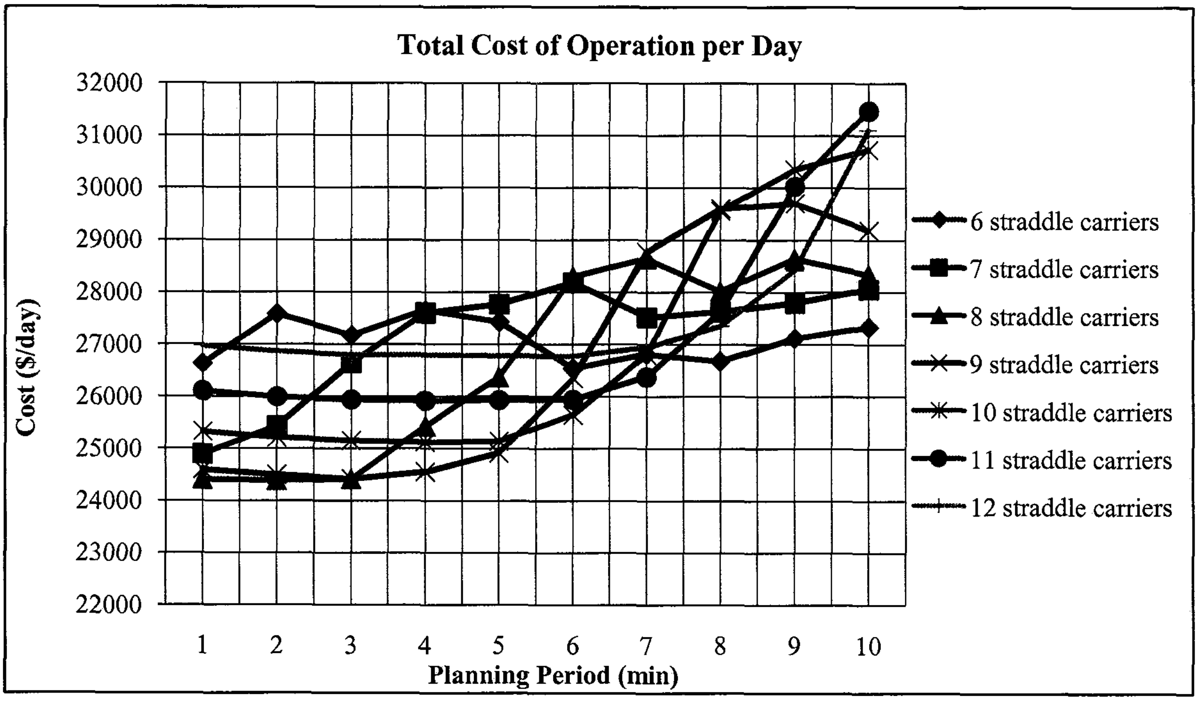

Figure B.2.8 Total cost of operation per day for arrival rate of 75 trucks per hour

The average truck waiting time for service is 2 minute and 11 seconds (Appendix B Table B.1.3). Average waiting time and time required to process all trucks (Figures B.2.9 and B.2.10) have an increasing trend as the planning period changes from 1 to 10 minutes.

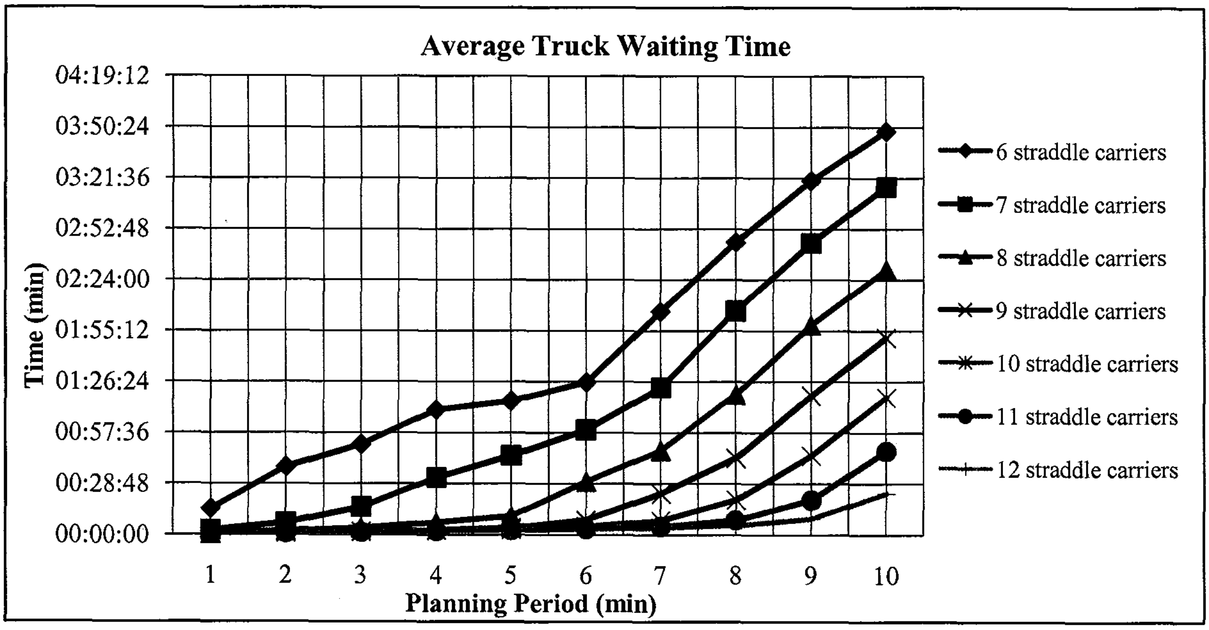

Figure B.2.9 Average truck waiting time for service for arrival rate of 75 trucks per hour

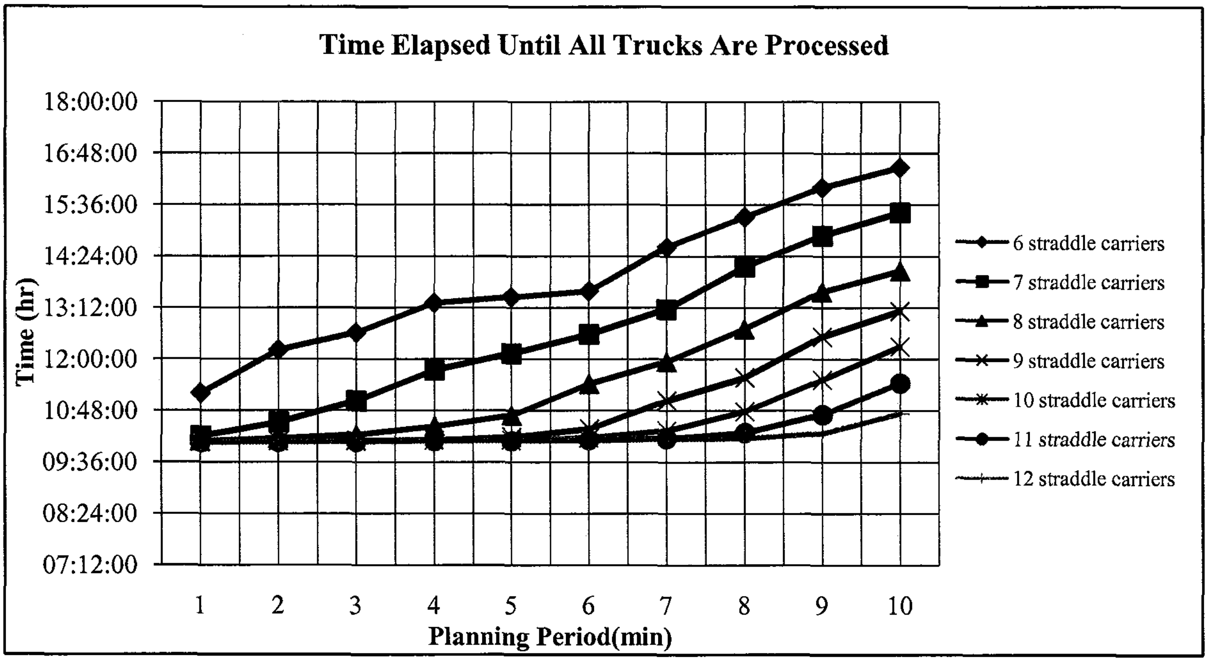

Figure B.2.10 Time elapsed until all trucks are processed for arrival rate of 75 trucks per hour

B.2.4 Simulation Results Based on Truck Arrival Rate of 100 trucks per hour

The optimal solution for the arrival rates of 100 trucks per hour was achieved with fleet size of 10 straddle carriers and with the duration of the planning period of 2 minutes (Figures B.2.11).

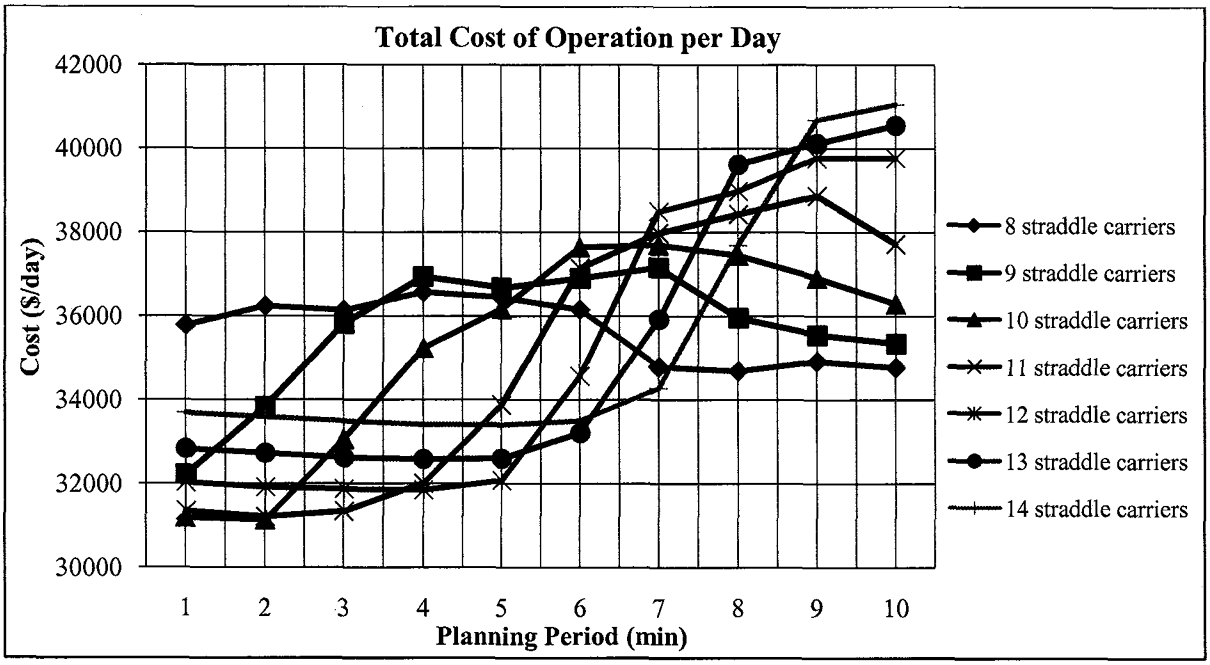

Figure B.2.11 Total cost of Operation per day for arrival rate of 100 trucks per hour

Average truck waiting time and time elapsed until all trucks are processed are shown on Figure B.2.12 and Figure B.2.13 respectively.

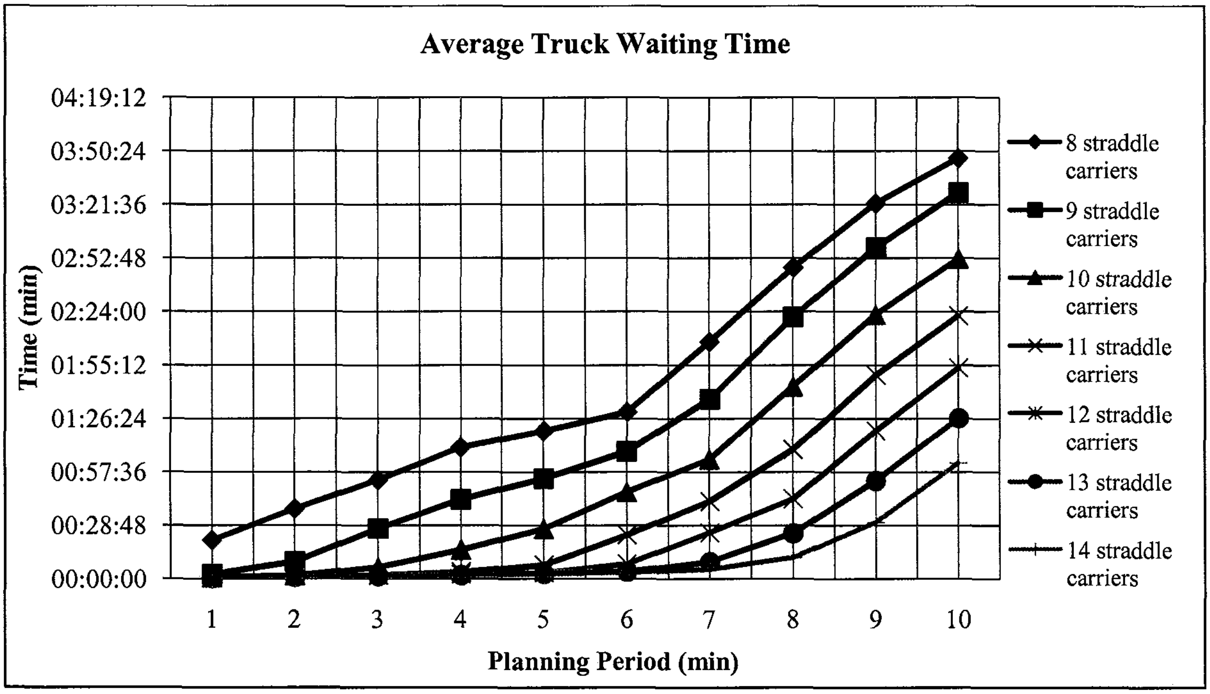

Figure B.2.12 Average truck waiting time for service for arrival rate of 100 trucks per hour

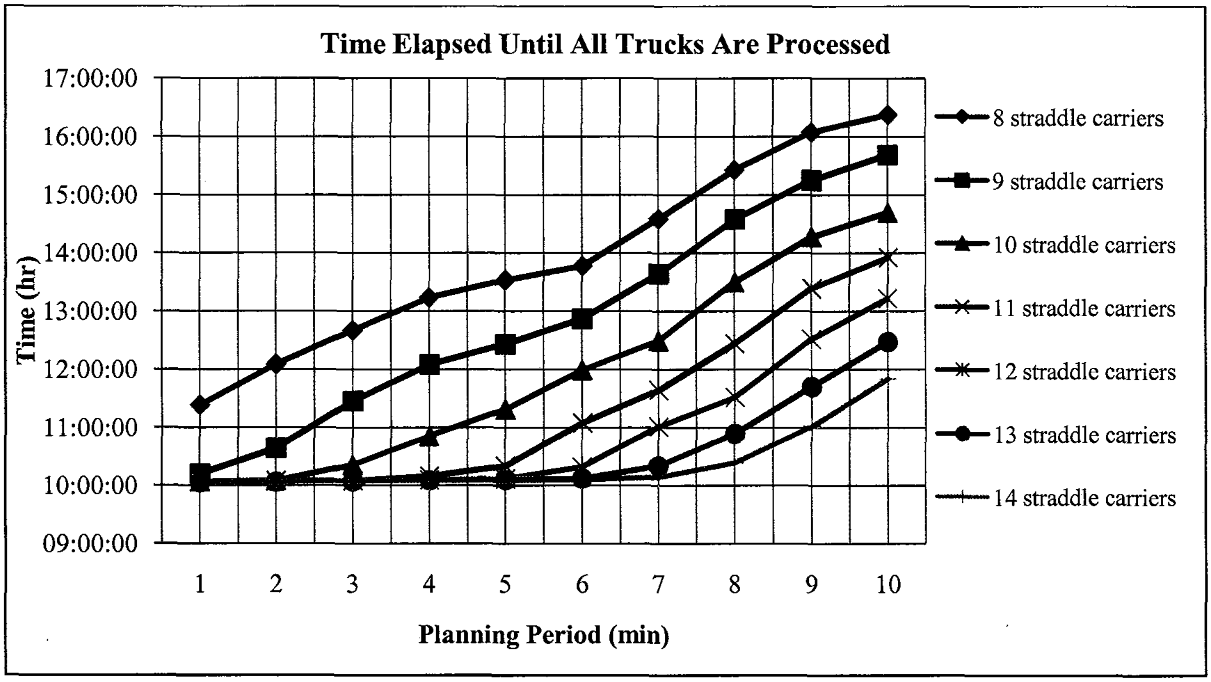

Figure B.2.13 Time elapsed until all trucks are processed for arrival rate of 100 trucks per hour

B.2.5 Simulation Results Based on Truck Arrival Rate of 125 trucks per hour

The arrival rate increase from 100 trucks per hour to 125 trucks per hour resulted in adding two additional straddle carriers to accommodate new service requests. The planning period duration remained the same at 2 minutes. Figure B.2.14 shows the change in the total daily cost as a function of the planning period and straddle carrier fleet size. The minimum cost is achieved with 13 straddle carriers in operation being considered for assignment every 2 minutes.

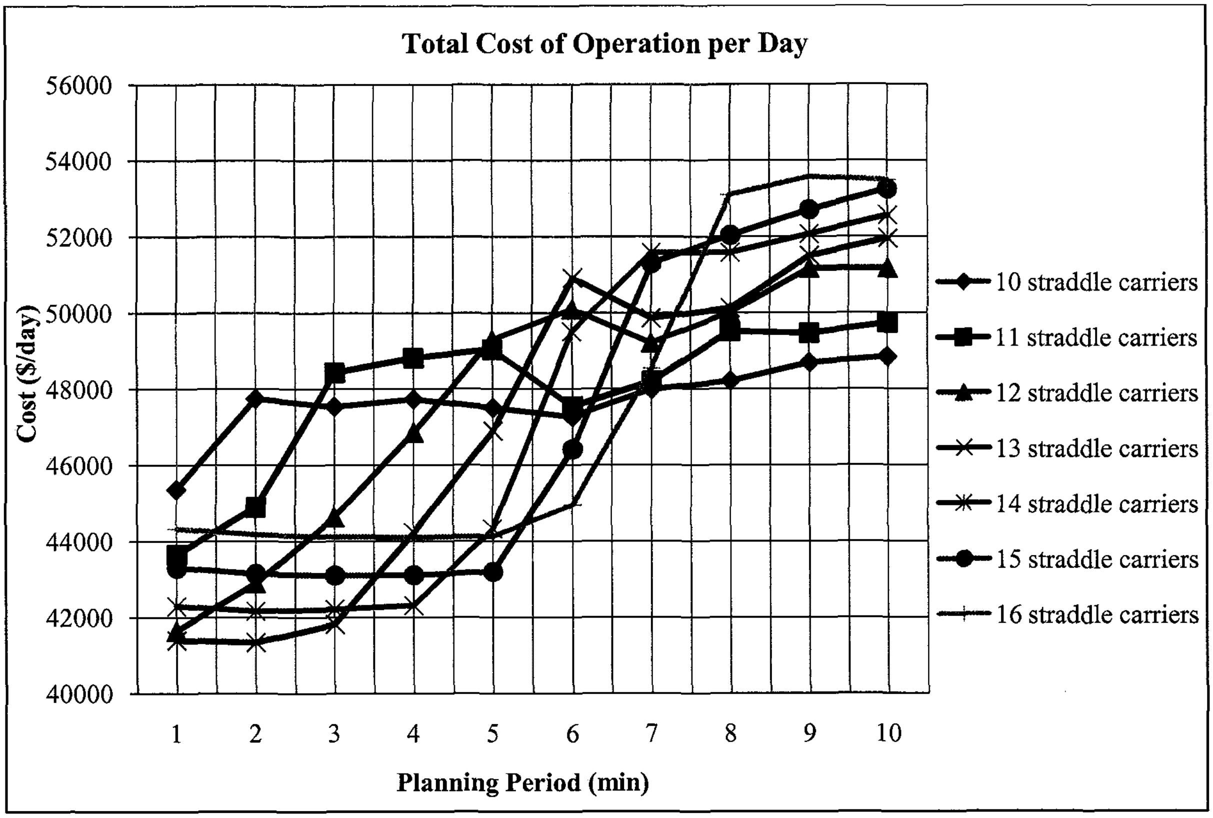

Figure B.2.14 Total cost of operation per day for arrival rate of 125 trucks per hour

To process all trucks, straddle carriers are remaining in operation for additional 56 seconds considered as overtime. Average truck waiting time and time elapsed until all trucks are processed are shown on Figure B.2.15 and Figure B.2.16 respectively.

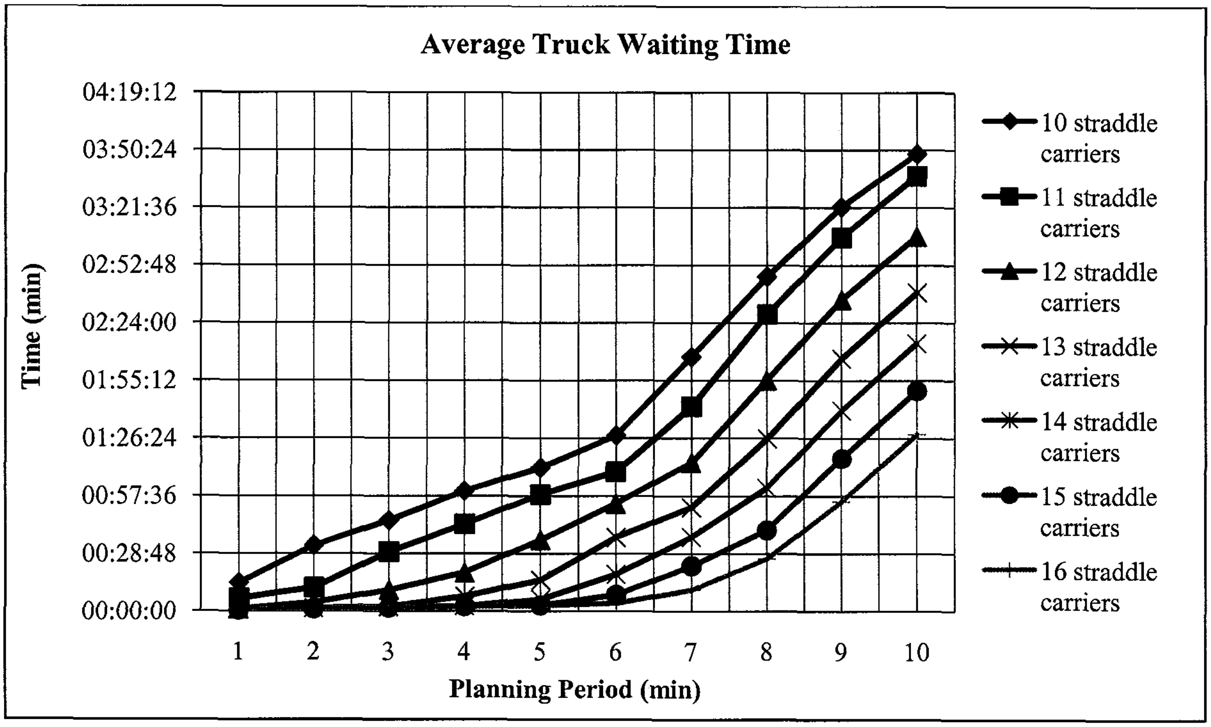

Figure B.2.15 Average truck waiting time for service for arrival rate of 125 trucks per hour

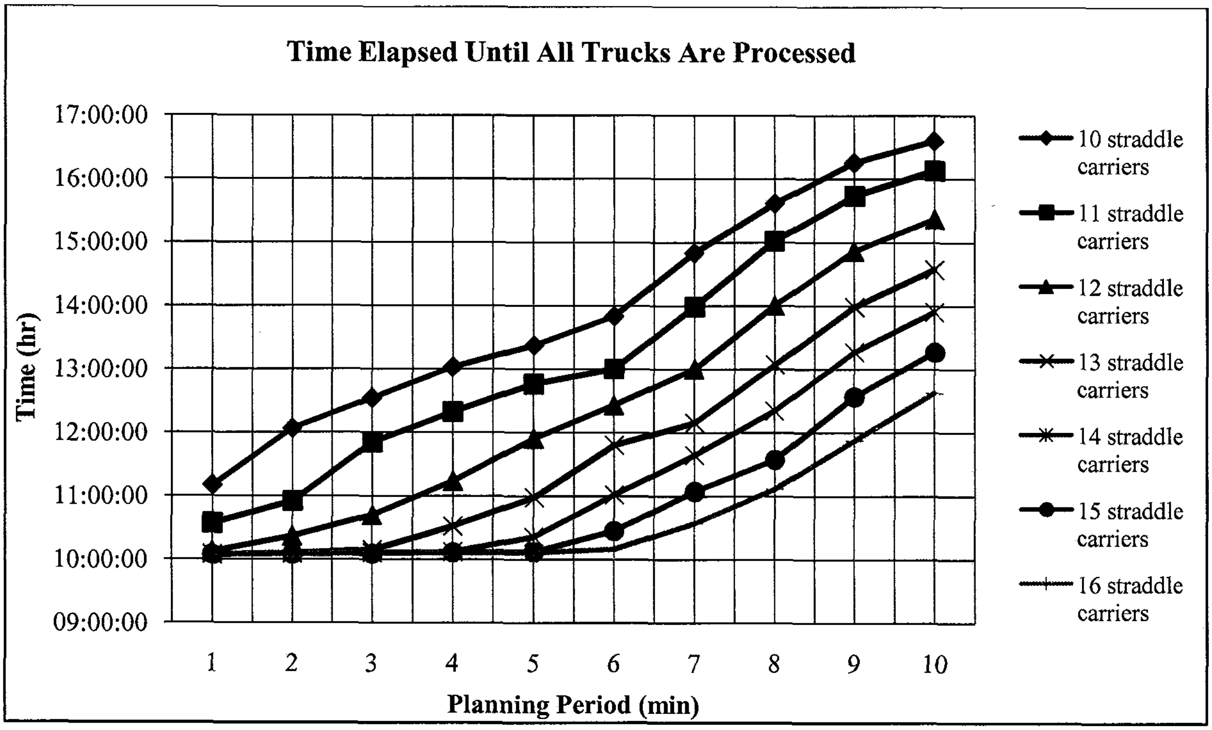

Figure B.2.16 Time elapsed until all trucks are processed for arrival rate of 125 trucks per hour

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