2018

Development Of Models And Solution Methods For Different Drayage Applications

Samaneh Shiri
University of South Carolina

DEVELOPMENT OF MODELS AND SOLUTION METHODS FOR DIFFERENT DRAYAGE APPLICATIONS

by

Samaneh Shiri

Bachelor of Science
University of Tehran, 2004

Master of Science
Iran University of Science and Technology, 2008

Submitted in Partial Fulfillment of the Requirements

For the Degree of Doctor of Philosophy in

Civil Engineering

College of Engineering and Computing

University of South Carolina

2018

Accepted by:

Nathan Huynh, Major Professor

Robert Mullen, Committee Member

Juan Caicedo, Committee Member

Pelin Pekgun, Committee Member

Cheryl L. Addy, Vice Provost and Dean of the Graduate School

DEDICATION

To my parents, Kimia and Akbar, and my siblings, Samira, Sahar, and Saeed.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere appreciation and gratitude to my advisor, Dr. Nathan Huynh, who supported my scientific interests and guided me expertly toward completion of this dissertation. I am truly fortunate to study under his guidance. His advice, both on research and my career have been priceless.

I would also like to acknowledge my committee members, Dr. Robert Mullen, Dr. Juan Caicedo, and Dr. Pelin Pekgun for their advice and feedback on this dissertation.

Also, I would like to thank the National Science Foundation (NSF) and South Carolina Department of Transportation (SCDOT) for supporting my graduate study at the University of South Carolina.

Last but not least, I would like to thank my family. None of this would have been possible without their endless love, support, and encouragement.

ABSTRACT

In the last decades, intermodal freight transport is becoming more attractive in the global supply chains and freight transport policy makings. Intermodal freight transport provides a cost-effective, reliable, and efficient movement of freight by utilizing the strengths of different transport modes. The initial and final segment of intermodal freight transport, performed by truck, is known as "drayage." The scheduling of truck movements in drayage operation within the service area of an intermodal terminal is an operational problem which leads to a truck scheduling problem that determines the efficient schedule of trucks while satisfying all transportation demands and constraints. Drayage accounts for a large percentage of the origin-destination expenses in the intermodal transport. Efficient planning of the drayage operations to improve the economic performance of this operation can increase the efficiency and attractiveness of intermodal transport. The primary objective of this research is to apply operation research techniques to optimize truck movements in drayage operation.

The first study in this dissertation considers the drayage problem with time constraints at marine container terminals imposed by the truck appointment system and time-windows at customer locations. A mathematical model is proposed that solve the empty container allocation problem, vehicle routing problem, and appointment booking problem in an integrated manner. This model is an extension of a multiple traveling salesman problem with time windows (m-TSPTW) which is known to be NP-hard (i.e., non-deterministic polynomial-time hard). To solve this model, a reactive tabu search

(RTS) algorithm is developed and its accuracy and computational efficiency are evaluated against an industry-established solver IBM ILOG CPLEX. In comparison with the CPLEX, RTS was able to find optimal or near-optimal solution in significantly shorter time. This integrated approach also allows for more accurate evaluation of the effects of the truck appointment system on the drayage operation.

The second study extends the drayage literature by incorporating these features in drayage problem: (1) treating tractor, container, and chassis as separate resources which are provided in different locations, (2) ensuring that container and chassis are of the same size and type, (3) considering the possibility that drayage companies can sub-contract the work to owner-operators, and (4) a heterogeneous mix of drayage vehicles (from company fleet and owner-operators) with different start and end locations is considered; drayage company's trucks start at company's depot and should return to one of the company's depots whereas owner-operators' trucks should return to the same location from where they originated. A mixed-integer quadratic programming model is developed that solves scheduling of tractors, full containers, empty containers, and chassis jointly. A RTS algorithm combined with an insertion heuristic is developed to tackle the problem. The experimental results demonstrated the feasibility of the developed model and solution methodology. The results show that the developed integrated model is capable of finding the optimal solutions and is solvable within a reasonable time for operational problems. This new model allowed us to assess the effectiveness of different chassis supply models on drayage operation time, the percentage of empty movements and air emissions.

The third study of this dissertation addresses the impact of a new trend in the North American intermodal terminals in using second-tier facilities on drayage operation. These facilities are located outside the terminals and are used to store loaded containers, empty containers, and chassis. This work builds on our previous work and extends the integrated drayage scheduling model to incorporate these features into drayage problem: (1) trucks do not have to wait at customers' locations during the packing and unpacking operations, (2) drayage operations include a drop yard (i.e., second-tier facility) for picking up or/and dropping off loaded containers outside the marine container terminal, and (3) the job requests by customers is extended to include empty container pickup, loaded container pickup, empty container delivery, and loaded container delivery. As the mathematical model is an extension of the m-TSPTW, a RTS combined with an insertion heuristic developed by the authors is used to solve the problems.

The fourth work builds on our previous work and extends the integrated drayage scheduling model to consider uncertainty in the (un)packing operation. Recognizing the inherent difficulty in obtaining an accurate probability distribution, this paper develops two new stochastic drayage scheduling models without explicit assumption about the probability distributions of the (un)packing times. The first model assumes that only the mean and variance of the (un)packing times are available, and the second model assumes that the mean as well as the upper and lower bounds of the (un)packing times are available. To demonstrate the feasibility of the developed models, they are tested on problem instances with real-life characteristics.

Future work would address the real-time scheduling of drayage problem. It would assume trucks' locations, travel times, and customer requests are updated throughout the day. We would propose a solution approach for solving such a complex model. The solution approach would be based on re-optimization of the drayage problem and consist of two phases: (1) initial optimization at the beginning of the day, and (2) re-optimization during operation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Intermodal freight transportation (shown in Figure 1.1) is defined as the transportation of freight in a container from a shipper to a receiver (consignee) using at least two transport modes (Macharis and Bontekoning, 2004). Intermodal freight transportation has received an increased attention in freight transport policy-making, recently. By utilizing the strengths of multiple transport modes, the intermodal transport provides a more flexible, reliable, profitable, and sustainable service compare to classical mono transport. The intermodal transport can benefit from the economies of scale of vessels or trains and the flexibility of trucks (Dotoli et al, 2017).

Figure 1.1 illustrates an example of a door-to-door intermodal freight transport from a shipper to a final receiver. As shown in figure 1.1, an intermodal transportation chain consists of intermodal terminals, customer locations and transportation network. Container terminals include seaport or inland terminal that are interfaces between different transport modes and the transfer between modes are performed in them (Bektas and Crainic, 2007). Customers are shippers and receivers that are origin and destination of freight, respectively. Finally, freight is shipped through the transportation network which consists of railway, inland waterway, sea, or roadway.

Intermodal freight transportation has two parts: long-haul and short-haul transportation. The long-haul transportation consists of container movement from origin terminal to destination terminal. This part of transport is carried out by a barge, train, ocean-going vessel or airplane. The short-haul of container transportation consists of two segments: pre-haul and end-haul. Pre-haul consists of moving a container from a shipper's location to an intermodal container terminal. End-haul consists of moving a container from an intermodal container terminal to a receiver's location. The short-haul of container transportation is typically carried out by trucks and is known as "drayage." The word "drayage" comes from "dray" which originally meant "a low, strong cart without fixed sides, for carrying heavy loads" (Ileri, 2006). For completing the container transportation from shipper to receiver, the drayage service by trucks is critical as modes such as vessels and trains cannot provide door-to-door services.

Figure 1.1 Illustration of intermodal freight transport (images were taken from Dreamstime's and Freepik's websites)

In the last decades, the expanding global economy has led to a rapid growth in container shipment. In 2015, U.S. waterborne foreign container trade in U.S. customs ports (including import and exports) was about 32 million twenty-foot equivalent units[1] (TEUs) which was approximately 12% more than trade in 2010 (MARAD, 2017). The average drayage trip legs for each container is about 2.5 (NCFRP Report 11), which shows there were over 80 million drayage trip legs for 32 million containers (TEUs) handled at U.S. ports in 2015. According to the American Trucking Associations (ATA), freight volumes will continue to increase in next decade (Rezaeifar et al., 2017).

Despite the relatively short distance of the drayage (i.e., short-haul transportation) compared to long-haul transportation, drayage constitutes a large part of the total costs of the intermodal transport; between 25% and 40% of the origin to destination expenses (Macharis and Bontekoning, 2004). The reasons of this high cost can be: 1) drayage operation by trucks cannot benefit from the economies of scale like vessels or trains (Escudero-Santana et al., 2015), and 2) non-revenue generating movements of empty container and empty vehicle are inevitable part of drayage services (Braekers et al., 2014). Minimizing the non-revenue generating movements of the trucks and increasing the efficiency in the drayage operation would increase economic performance of the drayage operation. Reducing drayage cost, as large portion of intermodal transportation cost, can play a critical role in improving the profitability of an intermodal transportation to benefit from its cost savings, environmental advantage, and highway safety results. In addition, inefficiencies in drayage operation results in negative regional effects like diesel engine emissions, congestion, noise, and safety hazards to the surrounding area. Specifically, increases in the volumes of freight traffic at intermodal terminals in metropolitan areas made these negative effects worse. Finally, because drayage trucks operate primarily in

[1] Based on International Standards Organization (ISO), a twenty-foot equivalent unit is an 8ft wide, 8.5ft high, and 20ft long container (Jula et al., 2005).

urban environments, a reduction of these harmful impacts has a proportionally greater benefit.

Several studies have applied operation research techniques to optimize the movement of trucks in drayage operation. This dissertation focuses on the integrated version of drayage problem and it extends the previous drayage literature in six aspects: 1) considering a time window constraints at marine container terminals via the truck appointment system, 2) considering chassis as a separate resource which should be provided in drayage operation, 3) considering different container sizes in drayage problem and ensuring that container and chassis are of the same size and type, 4) considering the possibility that drayage companies can subcontract the work to independent owner-operators whose trucks will originate from and terminate at different locations, 5) assuming the drop yards and second-tier facilities outside the intermodal terminal for picking up and delivering the empty/full containers and chassis, and 6) assuming uncertainty in drayage operations.

1.1 RESEARCH TOPIC I – OPTIMIZATION OF DRAYAGE OPERATIONS WITH TIME WINDOW CONSTRAINTS

In an effort to reduce gate congestion and to reduce truck turn time inside the intermodal terminal, terminals such as those at the Port of Vancouver are requiring trucks to have an appointment. The truck appointment system poses a significant challenge to drayage firms that in addition to satisfying the need to pick or drop off a container at a customer location within a specified time window, they must also choose an appointment time window at the terminal such that it minimizes their operational time. The first study addresses this practice by considering time window constraints at marine container terminals via a truck appointment system. A mixed-integer quadratic programming model that is an extension of the multiple traveling salesman problem with time windows (m-TSPTW) is proposed. Since this model is NP-hard (non-deterministic polynomial-time hard), a reactive tabu search algorithm (RTS) combined with an insertion heuristic was developed to solve the integrated model. The experimental results indicated that RTS can find the optimal solutions for small-sized problem and can solve operational problems within reasonable time. Readers are referred to chapter 3 of this dissertation for comprehensive information about this work.

1.2 RESEARCH TOPIC II – ASSESSMENT OF U.S. CHASSIS SUPPLY MODELS ON DRAYAGE PRODUCTIVITY AND AIR EMISSIONS

Chassis is a wheeled structure that supports containers when they are transported by trucks and are provided in drayage service. The second study incorporated chassis allocation problem into the drayage scheduling problem. Also, it is assumed that drayage companies can subcontract the work to independent owner-operators whose trucks will originate from and terminate at different locations. A mixed-integer quadratic programming model that is an extension of the m-TSPTW is proposed. A RTS combined with an insertion heuristic was developed to solve the integrated optimization model. The comparison of RTS results with CPLEX demonstrated that the developed RTS can provide optimal solutions for the small-sized problem and can obtain near-optimal solutions in a faster time for medium and large-sized instances. The developed integrated model allowed us to examine the impact of different chassis supply models on the drayage operation time, percentage of empty movements, and air emissions. Readers are referred to chapter 4 of this dissertation for comprehensive information about this work.

1.3 RESEARCH TOPIC III – IMPACT OF SECOND-TIER CONTAINER PORT FACILITIES ON DRAYAGE OPERATION

This work aims to study the impact of second-tier facilities on drayage operation. Establishment of auxiliary or satellite facilities to store, stage, or transfer loaded containers, empty containers, and bare container chassis outside port container terminal is an observable trend in the North American terminals. These new "second-tier" facilities usually have shorter queues and shorter turn times than the intermodal terminals themselves but add legs to drayage truck trips. To determine the impact of second-tier facilities on drayage operation, this study builds on our previously developed drayage scheduling model and incorporating these features: (1) drayage operations includes second-tier facilities for picking up or/and dropping off loaded containers outside the marine container terminal, (2) trucks do not have to wait at customers' locations during the packing and unpacking operations, and (3) a customer is allowed to request any of the following jobs: empty container pickup, loaded container pickup, empty container delivery, and loaded container delivery. To solve this model, a RTS combined with an insertion heuristic developed by the authors is used. Readers are referred to chapter 5 of this dissertation for comprehensive information about this work.

1.4 RESEARCH TOPIC IV – INTEGRATED DRAYAGE SCHEDULING PROBLEM WITH STOCHASTIC CONTAINER PACKING AND UNPACKING TIMES

This study addresses a stochastic version of drayage scheduling problem to reflect possible uncertainty in drayage operations. The (un)packing times at customer locations are assumed to be uncertain. As finding the accurate probability distribution for the (un)packing times is difficult, this work proposed two stochastic drayage scheduling models using chance-constrained programming without explicit assumption about the probability distributions of the (un)packing times. The first model needs the specification of the mean and variance of the (un)packing times, and the second model needs the specification of the mean as well as the upper and lower bounds of the (un)packing times. To make the problem tractable, the chance constraints in models were converted to their deterministic equivalents using Cantelli's and Hoeffding's inequalities. To demonstrate the feasibility of the developed models, they are tested on problem instances with real-life characteristics. CPLEX is used to solve small-sized problems and a RTS combined with an insertion heuristic (developed by the authors) is used to solve medium and large-sized problems. Readers are referred to chapter 6 of this dissertation for comprehensive information about this work.

1.5 RESEARCH TOPIC V (FUTURE WORK) – REAL-TIME SCHEDULING OF DRAYAGE PROBLEM

Advanced information and communication technologies have provided the opportunity to manage drayage trucks in real-time. Future work would further enhance aforementioned models to represent reality by considering a real-time scheduling of the drayage problem. It would assume trucks' locations, travel times, and customer requests are updated throughout the day. Also, it would assume that there is a real-time communication between the driver and the decision maker to update the truck schedules when a new job arrival or an interruption occurs. An approach based on re-optimization of the drayage problem would be developed which consists of initial optimization at the beginning of the day, and re-optimization during operation. To demonstrate the feasibility of the developed solution methodology, it would be tested on problem instances with real-life characteristics. Readers are referred to chapter 7 of this dissertation for information about this work.

1.6 LIST OF PAPERS AND STRUCTURE OF DISSERTATION PROPOSAL

This dissertation includes results that have been published, accepted and submitted to peer-reviewed journals as well as presented in conferences in the related field of study. Followings are lists of published, accepted, and submitted papers that appear in the dissertation as separate chapters:

1. Shiri, S., Huynh, N., 2016. Optimization of drayage operations with time-window constraints. International Journal of Production Economics, 176, 7-20.

2. Shiri, S., Huynh, N., 2017. Assessment of U.S. chassis supply models on drayage productivity and air emissions. Transport. Res. Part D.

3. Shiri, S., Smith, D., N, Huynh, N., Harder, F., Impact of second-tier container port facilities on drayage operation. Submitted in Transportation Research Part E.

4. Shiri, S., Ng, N, Huynh, N., Integrated Drayage Scheduling Problem with Stochastic Container Packing and Unpacking Times. Accepted to be published in Journal of the Operational Research Society. DOI: 10.1080/01605682.2018.1457487.

Followings are lists of papers presented in conferences in the related field:

1. Shiri, S. and Huynh, N., 2015. An Agent-Based Approach to Solve the Daily Drayage Problem, 19th Annual Meeting on Agent-Based Modeling & Simulation.
2. Shiri, S. and Huynh, N., 2015. Planning of Container Movement by Trucks in Metropolitan Area, INFORMS Annual Meeting annual meeting.
3. Shiri, S. and Huynh, N., 2016. Drayage Scheduling with Time Window Constraints at Customer Locations and Marine Container Terminal. Transportation Research Board 95th Annual Meeting.
4. Shiri, S. and Huynh, N., 2016, The Impact of U.S. Chassis Supply Models on Drayage Productivity, INFORMS Annual Meeting.
5. Shiri, S. and Huynh, N., 2017. The Implications of U.S. Chassis Supply Models for Chassis Stakeholders, Transportation Research Board 96th Annual Meeting of the Transportation Research Board.
6. Shiri, S. and Huynh, N., 2017, Impact of Free-flow Operation on Drayage Productivity, INFORMS Annual Meeting.
7. Shiri, S., Smith, D., Huynh, N., and Harder, F., 2018, Emergence and Impacts of Second-Tier Container Port Facilities, Proceeding of 97th Annual Meeting of the Transportation Research Board.
8. Shiri, S., Ng, M., Huynh, N., 2018. Distribution-Free Scheduling of Drayage Operation under Uncertainty, Proceeding of 97th Annual Meeting of the Transportation Research Board.

The format of this dissertation follows a manuscript style and the remaining chapters are organized as follows. Chapter 2 provides a brief overview of drayage operations and methodologies used in this dissertation. Chapters 3, 4, 5, and 6 include four original research papers mentioned above and Chapter 7 presents the future work. Finally, Chapter 8 concludes the dissertation.

CHAPTER 2: BACKGROUND AND METHODOLOGY

This chapter provides the necessary background information related to the drayage operation and methodologies used in this study.

2.1 DRAYAGE OPERATION RESOURCE

Drayage operation involves the movement of multiple resources between customers' location, intermodal terminal and equipment yards. Followings are transportation resources which are provided in drayage operation:

- *Tractor*: the tractor (shown in Figure 2.1a) is a power unit that provides power for hauling a towed load (GCCG, 2017). The drayage company can either utilize its own drivers to drive the tractor or sub-contract the work to the owner-operators who provide their own tractor. The drayage company's tractors are initially located at one of the company's depots and should return to one of the company's depots whereas owner-operators' trucks are initially located at owner-operators' facilities and should return to the same facility where they originated.
- *Container*: the container (shown in Figure 2.1b) is a metal boxes structure that is used to transport freight as one unit. Containers have enabled a better management of cargo by 1) reducing freight damage as it is a strong metal box, and 2) speeding-up cargo handling and transfer operation as they have

standard structures and fit devices for transfer (Bektas and Crainic, 2007). Intermodal containers are sized according to International Standards Organization (ISO) (Vidović et al., 2011). 20-ft and 40-ft containers are the widely used container size over the world, while larger size of the container such as 45-ft container is allowed in the U.S. and Canada (Popović et al., 2014). Traditionally, containers were stored inside the intermodal terminal. But recently, there is an observable trend in the North American intermodal terminals toward the establishment of auxiliary or satellite facilities to store, stage, or transfer empty containers outside the terminal to improve terminal throughput. For example, at the Port of Vancouver, B.C., around 75% of empty containers are held in off-terminal depots.

- *Chassis*: the chassis (shown in Figure 2.1c) is a wheeled structure composed of a steel frame, tires, brakes, and a lighting system that supports containers when they are transported by a tractor. Container chassis in the U.S. have a fixed size to support a specific container size; that is, a 20-ft container needs to be transported with a 20-ft chassis and a 40-ft container needs to be transported with a 40-ft chassis. In the U.S., the ratio of 20-ft to 40-ft to 45-ft chassis is 25:65:10 (NCFRP Report 20). In addition to standard chassis, there are specialty chassis. For example, refrigerated containers require chassis equipped with a generator to provide electric power to the containers. Historically, chassis are owned and operated by ocean carriers and stored within the terminals in the U.S. Recently, many ocean carriers seek to exit the chassis supply business. The transition to new chassis supply models has changed supply, ownership, and management of chassis. According to NCFRP Report 20, currently, there are five different chassis supply models in the U.S.: ocean carrier, co-op pool, rental pool, terminal pool and motor carrier. Readers are referred to chapter 4.1 of this dissertation for comprehensive information about these models.

(a) (b) (c)

Figure 2.1 Transportation resources in drayage operation: (a) Tractor (source: Ryder's website); (b) Container (source: Intercon Modular' website); (c) Chassis (source: Cheetah chassis's website)

2.2 DRAYAGE PROBLEM DESCRIPTION

This study addresses the scheduling decision to be made by the drayage company on a daily basis. Trucks visit following locations to provide drayage service: 1) truck depot or owner-operators' facilities, 2) intermodal container terminal, 3) equipment yards (i.e., empty container depot and/or chassis yard), and 4) customers' locations. A customer is either a shipper or a receiver that procuring the service of a drayage company to deliver an export container or to pick up an import container, respectively. Figure 2.2 shows a typical journey for drayage trucks in drayage operation for shipper (i.e., export delivery) and receiver (i.e., import pickup). Figure 2.2a illustrates the logistic process of bringing a container from a shipper’s location to an intermodal terminal in drayage operation (i.e., Steps E_1 to E_4).

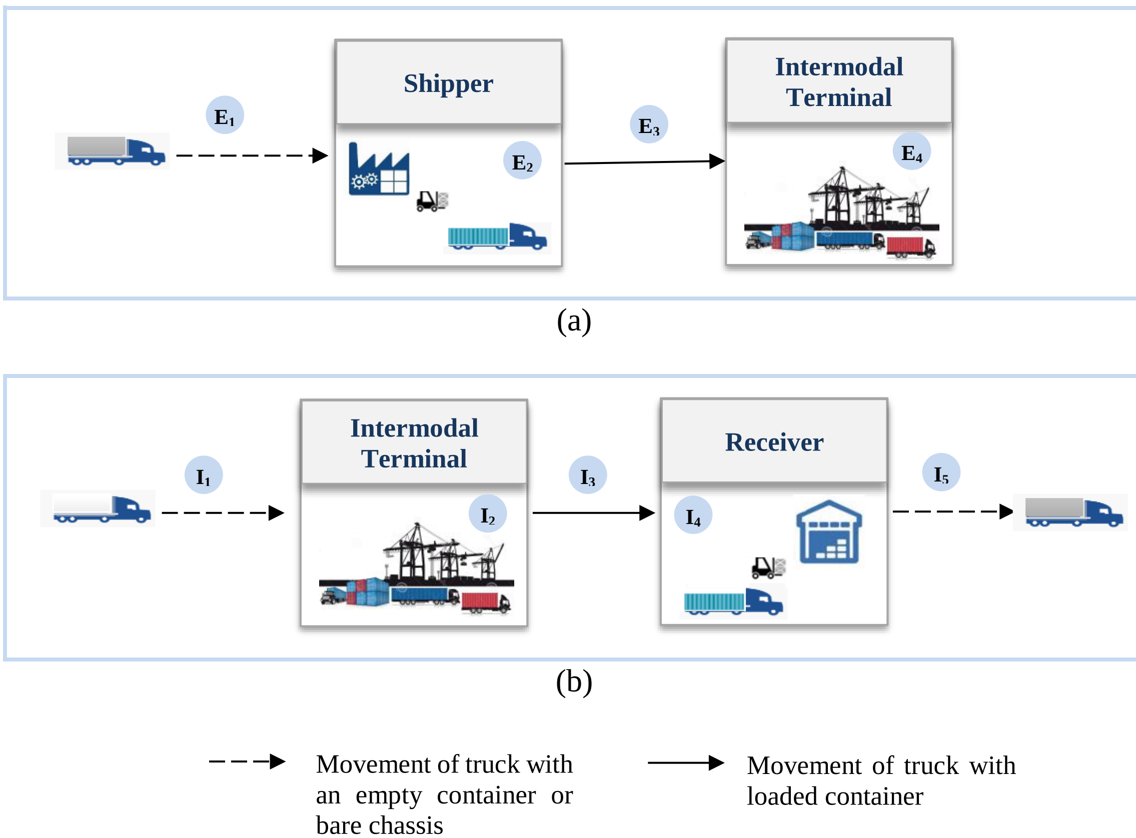


Figure 2.2 Movement of truck in drayage operation: (a) export delivery; (b) import pickup

First, a truck transports an empty container from an empty container depot or from another customer’s location to the shipper’s location (Step E_1) where customer packs freight to the container. Then, a truck picks up the loaded container from the customer’s location (Step E_2) and transports it to the intermodal terminal (Step E_3). At the terminal, truck waits at the terminal gate to enter the terminal and drop off the loaded container to the terminal (Step E_4) where it will get loaded onto a container vessel or train to be transported to its next terminal. Figure 2.2b illustrates the logistic process of bringing a container from an intermodal terminal to a receiver' location (i.e., Steps I_1 to I_5). Once the container reaches its destination terminal, the container is unloaded and stored at the container terminal. The drayage sequence begins with sending a truck with a bare chassis to this terminal (Step I_1) where truck waits at the terminal gate to enter the terminal to pick up the loaded container (Step I_2). Then, the truck transports the loaded container to the receiver' location (Step I_3) where the container is unpacked. At the end, a truck picks up this empty container (Step I_4) and returns it to the empty container depot or transports it to another customer's location (Step I_5).

2.3 MATHEMATICAL PROGRAMMING

Mathematical programming is one of the most widely used technique in operational research and management science (Williams, 2013). The mathematical programming involves maximizing profit or minimizing costs subject to constraints on capacity, supply, etc. (Fourer et al., 2003). A mathematical programming problem has the following general formulation (Jeter, 1986).

Minimize (or Maximize) $f(x_1, x_2,..., x_n)$ (2.1)

Subject to (s.t.): $(x_1, x_2,..., x_n) \in \Omega$ (2.2)

where

x_i = decision variable i

Ω = a subset of the domain of f

$f(x_1, x_2, \ldots, x_n)$ in Equation (2.1) is referred to as the *objective function* and Ω shows the feasible region. The objective function is a function that specifies the criterion that evaluates alternative solutions to the problem. In a *constrained* problem, Ω is defined by a set of inequalities or equalities that reflect the *constraints* of the problem such as limited resources. Decision variables are a set of quantities that the decision makers would like to determine via solving the mathematical problem. The goal of the optimization problem is to find the values for decision variables that give the best value of the objective function and satisfy all constraints. When objective function and all constraints are in a linear form, the problem is called a *linear* programming model which is the most common and easiest type of programming model. The standard form of a linear model is as follows.

$$\text{Minimize} \quad \sum_{j=1}^{n} c_j \, x_j \tag{2.3}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} a_{ij} x_i \leq b_j \qquad j = 1, \ldots, m \tag{2.4}$$

$$x_j \geq 0 \qquad i = 1, \ldots, n \tag{2.5}$$

where

c_i, a_{ij} and b_j = constants

x_i = decision variable i

m = number of constraints

n = number of decision variables

When some variables are constrained to take integer values, the model becomes more complicated and is referred to as *mixed-integer* programming model. The problem becomes even more complicated when the objective function or/and constraints are non-linear. This type of problems is called *non-linear* programming models. A model that has a quadratic form of the objective function is called the *quadratic* programming problem.

The developed mathematical formulations in this study are mixed-integer quadratic programming models (MIQP). A series of commercial software can be used to solve this type of mathematical models. To obtain the exact solutions to validate our models and solution methodology, we used the commercial solver IBM ILOG CPLEX. The current version of CPLEX, 12.6.1, is capable of solving MIQP.

2.4 STOCHASTIC PROGRAMMING

Most real-life problems involve uncertainty; that is, most of the information in these types of problems are stochastic. To incorporate this stochastic nature of real-life problems to the mathematical programming, *stochastic* or *probabilistic* programming is used. In the stochastic programming, some or all parameters in the mathematical model (constants shown in Equations (2.3 and 2.4)) are stochastic (Rao and Rao, 2009). When a problem becomes stochastic, the objective function can be replaced by expected value and constraints are shown in term of the probability of the reaching the goal (Wallace and Ziemba, 2005). This type of problem is called *chance-constraint* program or problem with *probabilistic constraints* (Birge and Louveaux, 2011). In the *chance-constrained* programming model, constraints shown in Equation (2.4) are stated as follows (Rao and Rao, 2009).

$$P\left[\sum_{i=1}^{n} a_{ij} x_i \le b_j\right] \ge \Pi_j \qquad j = 1,\ldots,m \tag{2.6}$$

where

$\Pi_j \in [0,1]$ = probability

a_{ij} and b_j = random variables

The modified constraint is called *chance* or *probabilistic* constraint that guarantees constraint *j* is satisfied with probability at least Π_j (Williams, 1990). One of the methods for keeping the *chance-constrained* programming model tractable is converting the chance constraints to their deterministic equivalents (Liu and Iwamura, 1998). This will allow us to use linear programming technique to solve the stochastic models.

2.5 BASIC STATISTICAL CONCEPTS

The basic statistical concepts associated with the analysis in this work are described in this section.

Theorem (Cantelli's inequality): Let X be a random variable with $E(X) = \mu$ and $Var(X) = \sigma^2$, then Cantelli's inequality is as follows (Chen, 2015):

$$P(X - \mu \le \lambda) \begin{cases} \le \dfrac{\sigma^2}{\sigma^2 + \lambda^2} & \text{if } \lambda < 0 \\ \le 1 - \dfrac{\sigma^2}{\sigma^2 + \lambda^2} & \text{if } \lambda > 0 \end{cases} \tag{2.7}$$

Theorem (Hoeffding's inequality): Let $x_1, \ldots, x_n$ be independent random variable such that $x_i \in [a_i, b_i]$ for $i = 1, \ldots, n$. If $S_n = \sum_{i=1}^{n} x_i$ and $\mathrm{E}[S_n]$ is the expected value of S_n, then for all $t > 0$, the Hoeffding's inequality is as follows (Boucheron et al., 2013).

$$P\left(S_n - \mathrm{E}[S_n] \geq t\right) \leq \exp\left(\frac{-2t^2}{\sum_{i=1}^{n}(b_i - a_i)^2}\right) \tag{2.8}$$

In this work, two chance-constrained programming models were developed in research topics IV. To convert chance constrains to their deterministic equivalents, Cantelli's and Hoeffding's inequalities were used.

2.6 REACTIVE TABU SEARCH

The proposed mathematical models in this dissertation are NP-hard since they are an extension of the NP-hard problem m-TSPTW and meta-heuristics are widely used to solve similar problems. The proposed solution methodology in this research is based on the RTS algorithm (Battiti and Tecchiolli, 1994). While a number of meta-heuristics could be used to solve the proposed model, RTS is used in this study because it has been found to be successful in solving drayage problems (Zhang et al., 2009, 2011, 2015), as well as vehicle routing problems (Chiang and Russell, 1997; Osman and Wassan, 2002; Wassan et al., 2008). The solution method consists of two phases. Phase 1 generates an initial solution via a greedy heuristic and phase 2 seeks to obtain the optimal solution via the RTS. Figure 2.3 provides an overview of the developed solution methodology.

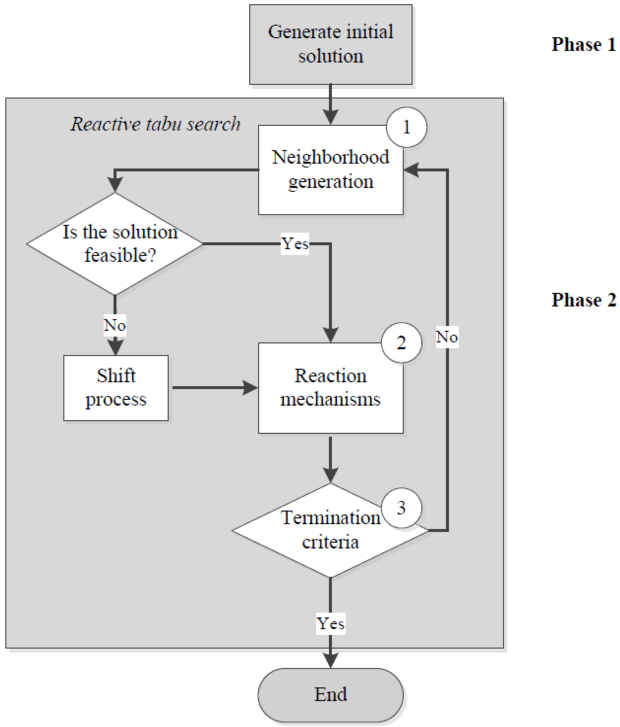


Figure 2.3 Flowchart of developed solution methodology.

Tabu search (TS) is a memory based metaheuristic which uses neighborhood search and prohibition-based techniques. During the exploration process, a collection of solutions is created by a set of moves that transforms one solution into another. A collection of adjacent solutions that can be reached from a solution is called a neighborhood. TS prevents cycling back to the previously visited solutions during the search by recording the recent history of moves as forbidden moves in a short-term memory list, called tabu list. The forbidden moves are kept in the tabu list for a period of time, known as tabu tenure. However, tabu restriction is not strict, it can be overridden when a tabu move results in a solution better than all visited solutions. Reactive search was introduced by Battiti et al. (1994) to improve TS by using the history of already visited solutions to guide the search. Tabu tenure is changed dynamically in RTS by tracking the number of repeated solutions.

Moreover, an escape mechanism is performed when the search is trapped in the solution space characterized as a “chaotic attractor basin”. In each chapter details of solution methodology for each specific problem are provided.

CHAPTER 3: OPTIMIZATION OF DRAYAGE OPERATIONS WITH TIME-WINDOW CONSTRAINTS[2]

[2] Shiri, S. and Huynh, N., 2016. Optimization of drayage operations with time-window constraints. International Journal of Production Economics, 176, pp.7-20.

ABSTRACT

This paper addresses a version of the drayage problem in which the intermodal terminal requires trucks to have an appointment, and each truck must pick up or drop off the container at a customer location within a specified time window. This problem is mathematically formulated as an extension of the multiple traveling salesman problem with time windows (m-TSPTW). To efficiently solve the model, an algorithm based on reactive tabu search (RTS) is developed. The RTS solutions demonstrate that the developed integrated model is capable of finding the optimal solutions and is solvable within a reasonable time for an operational problem. Experimental results indicate that (1) the appointment quota per time period set by the terminal operator has a significant effect on drayage operation time, (2) for a given change in appointment quota, there is no correlation between problem size and drayage operation time, (3) the adoption of an efficient truck appointment system could considerably reduce operation time for drayage firms, and (4) truck depots should be sited close to the terminal and empty container depot.

3.1 INTRODUCTION

The focus of this paper is on port drayage, which refers to the movement of containers between a marine terminal and an inland distribution point or rail terminal. A typical drayage assignment involves either delivering an export container (full or empty) to a marine terminal or picking up an import container (full or empty) from a marine terminal. The time it takes a driver to complete one such assignment includes: (1) travel time to marine terminals, (2) inbound gate queue time, (3) inbound gate processing time, (4) container yard transaction time, (5) outbound gate queue time, (6) outbound gate processing time, (7) travel time to customers (or depots or rail terminals), and (8) transaction time at customer locations (or depots or rail terminals). Additional time is required when the driver must first pick up a chassis before picking up the import container or drop off the chassis after delivering the export container. Figure 3.1 illustrates how spread out the drayage operation can be. In this instance, the container and chassis operations are taking place in separate locations.

Despite the relatively short distance of the drayage movement compared to the rail or barge haul, drayage accounts for a large percentage of origin to destination expenses. Drayage cost as a portion of the total door-to-door cost varies according to the length of the trip. According to Morlok and Spasovic (1994), the drayage cost for 500 and 1,500-mile haul are 42% and 22% of the total door-to-door cost, respectively. High drayage costs seriously affect the profitability of an intermodal service which in turn could impede the advance of intermodal freight transportation. Hence, it is important to improve drayage operations to keep costs low. Another important reason to improve drayage operations is to reduce its emissions impact on the surrounding communities due to engine idling and the stop-and-go lugging. Reducing the idling time of drayage trucks is equivalent to reducing local and regional particulate matter (PM 2.5), nitrogen oxides, and greenhouse gas emissions. Because drayage trucks operate primarily in urban environments, a reduction of these harmful pollutants has a proportionally greater benefit (Smith et al., 2012).

In an effort to reduce truck turn time and truck queuing at terminal gates, terminals such as those at the Port of Vancouver are requiring trucks to have an appointment system. The truck appointment system provides several key benefits to the terminal operators. One, it allows the terminal operators to match demands (container transactions) to supplies (labor and equipment availability). Second, it allows the terminal operators to evenly distribute truck arrivals throughout the day and hence reduce truck queuing at the gate. Lastly, the advanced entry of container and truck information via the appointment system expedites the processing of the trucks upon their arrivals to the terminal. While this new practice is beneficial to terminal operators and truckers, it poses a significant challenge to drayage firms who are already contending with a difficult drayage scheduling problem. Specifically, in addition to satisfying the need to pick or drop off a container at a customer location within a specified time window, the drayage firms must also choose an appointment time window at the terminal such that it minimizes their operational costs.

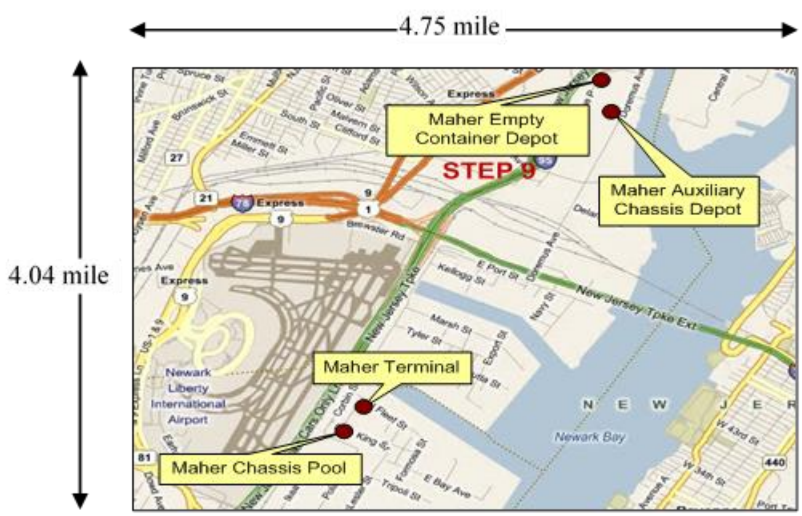


Figure 3.1 Layout of Maher container terminal and supporting depots at the Port of New York/New

This paper aims to address the aforementioned emerging practice by developing a new mathematical model for the drayage scheduling problem with time window constraints

(DSPTW) at customer locations and an appointment system at a marine container terminal. It assumes that all drayage operations use a single container type (i.e. 40-ft dry container) and that each truck carries a single container. The DSPTW is analogous to the multiple traveling salesman problem with time windows, but there are two key differences and challenges to modeling the DSPTW: (1) to complete a container transaction multiple locations may need to be visited, some of which are unknown *a priori* (e. g. the location of the empty container for the export-full transaction is not known *a priori*), and (2) the drayage firms need to book an appointment in advance prior to each visit to the container terminal. To solve the DSPTW, a reactive tabu search (RTS) algorithm is developed and its accuracy and computational efficiency is evaluated against an industry-established solver.

The rest of the paper is organized as follows. Section 2 provides a brief background on the drayage scheduling problem to provide context for this problem and to introduce a few relevant terminologies. Section 3 provides a review of related studies. Sections 4 provide the problem description and formulation. Section 5 presents the proposed solution methodology. Section 6 discusses the experimental results. Lastly, section 7 provides a summary of the study and concluding remarks.

3.2 LITERATURE REVIEW

Several studies have addressed the static and deterministic version of the drayage scheduling problem. Wang and Regan (2002) treated the drayage scheduling problem as a local truckload pickup and delivery problem and modeled it as an asymmetric multiple vehicle travelling salesman problem with time windows (am-TSPTW). They proposed a window partition-based method for solving the model. Jula et al. (2005) modeled the drayage scheduling problem as am-TSPTW as well. They added a new constraint that addresses the hours-of-service regulation. They developed three solution approaches: (1) an exact algorithm based on dynamic programming, (2) a hybrid methodology that combines dynamic programming and genetic algorithm, and (3) an insertion heuristic method. Imai et al. (2007) solved the truckload pickup and delivery problem that involves an intermodal terminal. They proposed a relaxation-based heuristic which consists of two sub-problems: the classical assignment problem and the generalized assignment problem. Caris and Janssens (2009) extended the work of Imai et al. (2007) by introducing time window constraints at customer locations and the depot. Their solution approach employed a two-phase insertion heuristic to generate the initial solution; in phase one pickups and deliveries are combined into pairs and in phase two these pairs of customers are inserted into routes. This initial solution is further improved with a local search heuristic. Namboothiri and Erera (2008) studied the effect of a terminal appointment-based access control systems at a port on container pickup and delivery service operations. Their solution approach used a heuristic with column generation to generate near-optimal solutions. Xue et al. (2014) considered the drayage problem in which trucks do not wait at customers' locations during the packing and unpacking operations. They formulated the problem as a vehicle routing and scheduling problem with temporal constraints. Their solution method is based on tabu search. Both Popović et al. (2014) and Zhang et al. (2015) investigated the multi-size container transportation problem. In the work by Popović et al. (2014), the authors proposed a variable neighborhood search heuristic to solve the problem. In the work by Zhang et al. (2015), the authors modeled the problem as a sequence-dependent multiple-traveling salesman problem with social constraints. They developed three tree search procedures and an improved reactive tabu search algorithm to solve the model. Their proposed search procedures can provide exact solutions for small-sized problems and their proposed reactive tabu search algorithm can solve realistic-sized problems efficiently.

In recent years, a number of studies have sought to solve the empty container allocation problem and vehicle routing problem in an integrated manner. Smilowitz (2006) modeled the integrated drayage scheduling problem as a multi-resource routing problem with flexible tasks. The author proposed a column generation method embedded in a branch-and-bound framework to solve the optimization model. Zhang et al. (2009) modeled the integrated drayage scheduling problem with multiple depots as am-TSPTW, and the authors solved it using a RTS algorithm. This work was extended by Zhang et al. (2010) who presented a window-partition based solution method inspired by Wang and Regan (2002). Zhang et al. (2011) built on their previous works and considered empty containers as transportation resources. They studied the integrated drayage scheduling problem where a single depot has a limited number of available empty containers. As in their past work, they utilized the RTS algorithm to solve their proposed model. Braekers et al. (2013) proposed a sequential and an integrated approach to solve the drayage problem. They developed a single-phase and a two-phase deterministic annealing algorithm to solve their proposed model. Their results showed that the integrated approach results are superior to those obtained by sequential approach. In their subsequent work, Braekers et al. (2014) considered two objectives with equal priority: (1) minimizing the number of vehicles, and (2) minimizing total distances. The problem is modeled as an asymmetric multiple vehicle traveling salesman problem with time windows. Three solution methods were developed to solve the model: (1) iterative, (2) deterministic annealing, and (3) hybrid of deterministic annealing and tabu search. They concluded that among the three methods the hybrid algorithm yielded the best results. Sterzik et al. (2015) investigated the effect of sharing empty container between trucking companies. They compared two scenarios: (1) trucking companies have access only to their own containers, and (2) trucking companies share empty containers between cooperating trucking companies. They proposed a tabu search heuristic to solve their proposed model. Their results showed that exchanging empty containers will yield lower total costs.

A few studies have addressed the dynamic and stochastic version of the drayage scheduling problem. Cheung and Hange (2003) assumed uncertainty in service times of tasks and formulated the problem as a stochastic model which seeks to minimize the current and future costs. To estimate the future costs the authors developed a time-window sliding procedure. Máhr et al. (2010) investigated the drayage scheduling problem with uncertainty in service-times and job-arrivals. They solved the problem by using an on-line optimization and an agent-based method. The on-line optimization method used a mixed integer program to obtain a new feasible route with newly captured information at 30 (s) intervals. The agent-based method used an auction scheme where container agents hold auctions in order of their arrivals and truck agents bid in these auctions. Zhang et al. (2011) studied the drayage scheduling problem where customer requests are not known a priori and developed a dynamic solution approach (the routing problem is solved at the beginning of the planning horizon and then updated at decision epochs). Real-time knowledge about the position of the vehicles is considered in the works by Escudero et al. (2011, 2013).

Their solution approaches involved taking snapshots of prevailing situations, use the captured information to update the state of all tasks and vehicles, and then rerun the optimization model. Wang and Kopfer (2015) investigated the dynamic version of the drayage problem in which companies can exchange customer requests (i.e. dynamic collaborative transportation planning). They proposed two rolling horizon planning approaches to solve the problem. Their results showed that collaborative transportation planning yielded better results than isolated planning.

The focus of this study is most closely related to the work performed by Namboothiri and Erera (2008) in that both focus on solving the drayage scheduling problem with explicit consideration of the truck appointment system. However, the key differences between their work and ours are: (1) our model accounts for drayage firms with multiple depots, and (2) our model considers the empty container allocation problem, vehicle routing problem and appointment booking problem in an integrated manner. Our formulation adapts and extends the work of Zhang et al. (2010) to address the DSPTW. The key extension and contribution is the consideration of the truck appointment system and drayage scheduling problem jointly (to address the emerging practice as previously explained in the Introduction section). To our knowledge, our proposed model is the first to solve the empty container allocation problem, vehicle routing problem and appointment booking problem in an integrated manner. This integrated approach will allow for more accurate evaluation of the effects of the truck appointment system on drayage operational costs.

3.3 DRAYAGE PROBLEM DESCRIPTION AND FORMULATION

This study considers the typical drayage model in the U.S. That is, a drayage firm owns a number of trucks which are used to transport containers for customers. The containers and chassis are supplied by the ocean carriers. Depending on the size of the drayage firm, the truck fleet may be divided into several sub-fleets, each of which is managed by a dispatcher and the sub-fleets could be located in different truck depots. The job of the dispatcher is to manage the sub-fleet to satisfy the container transportation orders between the customers' locations, the empty container depot and the marine container terminal. The dispatcher's job is further complicated by the fact that customers operate on certain time windows and that the container terminal requires trucks to make appointments in advance. The scheduling decision to be made by the dispatcher on a daily basis is the focus of this study (i.e. solving the DSPTW).

In this study, a customer is the shipper or consignee. A loaded container to be transported from a shipper to the container terminal is called an export, and a loaded container to be transport from the container terminal to the consignee is called an import. Figure 3.3a shows a typical journey of one drayage truck. In this example, there is one container terminal, one truck depot with two trucks, one empty container depot, and two customers (one shipper and one consignee). The job orders involve fulfilling an import order for the consignee and an export order for the shipper. The sequence of the drayage movements are indicated by the respective numbers on the line segments in Figure 3.3a. The sequence begins with the truck picking up the import full container from the container terminal and then delivering it to consignee where the container will be unpacked (the container will then be empty). The truck then transports the empty container to the empty container depot and return to its truck depot. To fulfill the shipper's order, the truck first picks up the empty container from the empty container depot and then transports it to the shipper's location where the container will be packed (the container will then be full). The truck then transports the loaded container to the container terminal and returns to its truck depot. In this example, the empty containers are picked up from and delivered to the empty container depot, but it could also be done at the container terminal. Regardless of where the empty containers are stored, the mentioned drayage movements are still necessary.

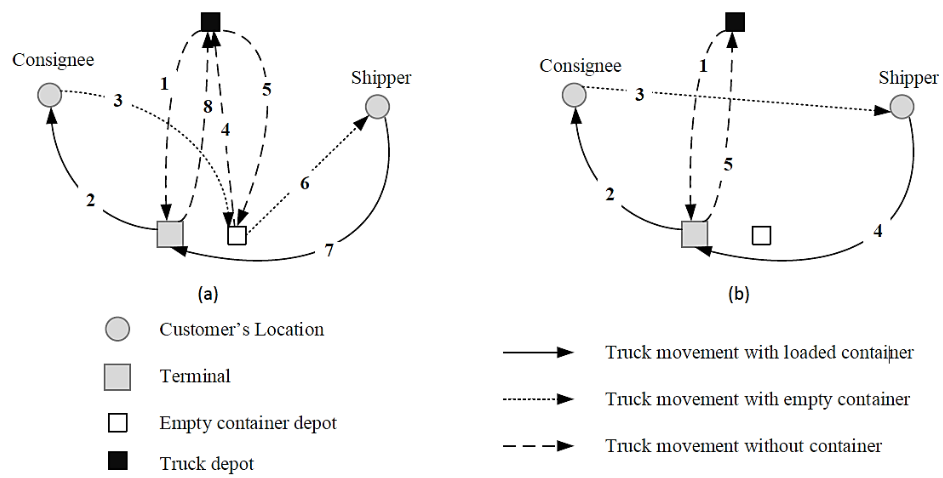


Figure 3.2 Illustration drayage truck movements: (a) without street turns; (b) with street turns

It can be observed in the aforementioned example (Figure 3.3a) that the shipper will typically need an empty container before shipping a loaded container and thus it would be more efficient if the truck were to deliver the empty container from the consignee to the shipper. This strategy is known as "street-turns" and implementing such a strategy will result in fewer gate transactions at the container terminal or empty container depot, better driver productivity and enhanced equipment utilization. Figure 3.3b illustrates the drayage movements for the same scenario using the street-turn strategy.

The aim of this study is to determine the optimal drayage sequence for each truck in a sub-fleet, considering street-turns, to fulfill all the transportation orders from customers. A customer is allowed to request one or more of the following jobs: import pickup and export delivery. In this study, we assume that trucks are required to stay at the customer's location during the packing and unpacking operation and one time window is considered at customer location. A similar assumption has been used in other studies, such as Zhang et al. (2010, 2011), and Escudero et al. (2011, 2013). However, it should be noted that if the packing and unpacking times are excessively long, then trucks will not stay at the customer locations. In that scenario, there will be two time windows at customer locations. An example study that uses this approach is the work by Xue et al. (2014). The considered time windows at customer location represents the time intervals in which the corresponding activities to customer location must be started. If a truck arrives at a customer location before the start of the specified time window, it must wait until that time window commences. Consequently, the total operation time includes travel, service and waiting time. This study models the truck appointment system the way that it is typically set up in practice in North American ports/terminals. That is, the appointment system is divided into multiple time periods in which the available number of quotas (i.e. number of trucks allowed) is predefined by the terminal operator. In current practice, the quota for each time period is applicable to both export and import containers. The drayage firms need to book appointments for trucks in advance (one day prior to dispatching a truck to the terminal). If the quota for the desired time period is exceeded, then they must choose a different time period. It is recognized that in other parts of the world (e.g. China), truck appointment systems (also known as vehicle booking systems) work differently and some are more advanced than the current state-of-the-practice in North America. For example, at some of these terminals, the operators set up the appointment system to coordinate truck arrivals with vessel schedules and not simply as a means to control truck entries. Examples of such works have been performed by Chen et al. (2010) and Chen and Yang (2010).

The drayage firm is considered to have multiple truck depots in which a limited number of trucks are located initially. All trucks must start at and return to one of these truck depots. The final truck depot does not have to be the same as the starting truck depot. We assume that trucks will choose the depot nearest to their last location as the final depot. We assume that all containers (empty and full) are of the same type (40-ft dry containers) and that empty containers are stored in the empty container depot and should be picked up from and delivered to this depot. It is assumed that there is a sufficient number of empty containers at the empty container depot.

3.4 BACKGROUND

Figure 3.2 provides an overview of the relationships between strategic, tactical, and operational decisions and models that have been developed in the literature to manage in-land container movements. The drayage scheduling problem addressed in this paper pertains to the operational models. Specifically, it deals with the empty container allocation (reposition) model and routing model. The empty container allocation model deals with repositioning empty containers. Its goal is to determine the optimal distribution of empty containers based on the locations of demand and supply (i.e. customer locations, container terminal, empty container depot, and truck depot). For additional Wang and Regan pertaining to empty container management, readers are referred to Braekers et al. (2011). As illustrated in Figure 3.2, the output of the empty container allocation model is then used as input to the routing model, which aims to determine the optimal tour to satisfy the pickup and delivery orders of loaded and empty containers. The objective of the routing model is typically to minimize the overall operational costs of transporting loaded and empty containers.

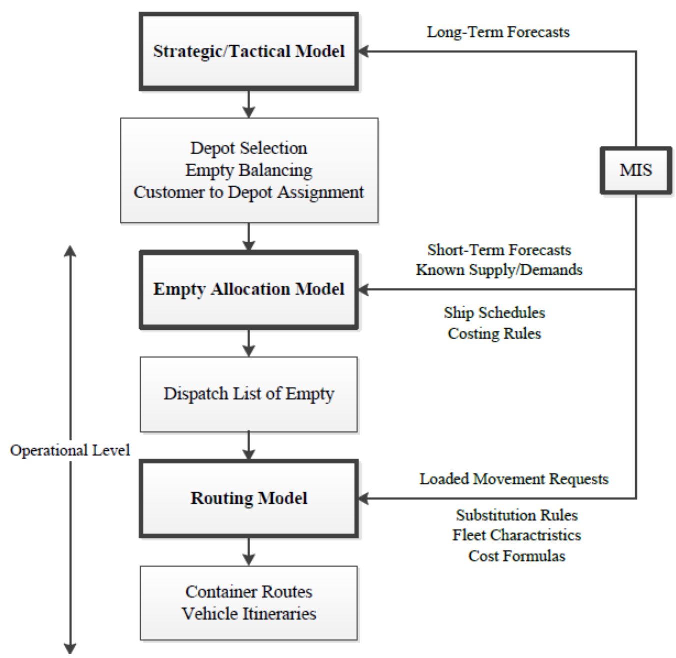


Figure 3.3 Overall planning approach of in-land container movements (adopted from Crainic et al., 1993).

3.4.1 Problem Parameters

N_D Set of truck depot nodes

N_I	Set of import job nodes
N_E	Set of export job nodes
N_J	Set of job nodes, $\{N_I \cup N_E\}$
T	Set of time periods at terminal
n_i	Number of trucks initially located at depot *i*
$[L_i^C, U_i^C]$	Time window of job node *i* at the customer's location
$[L_i, U_i]$	Time window of job node *i*
$\left[L_k^T, U_k^T\right]$	Time period *k* at terminal
Q_k	Number of terminal specified appointment quotas for each time period *k* (time period *k*'s capacity)
t_i	Total time of all activities before starting node *i*'s destination activities
ST_i	Service time of node *i*
TT_{ij}	Transfer time on arc *(i, j)*

3.4.2 Graphical Representation of the Drayage Problem

The formulation of the DSPTW is based on a graph representation of the various drayage activities. This graphical representation is adapted from the work of Zhang et al. (2010) which is an activity-based graph. Consider a network that is represented by a directed graph with a set of *N* nodes and a set of *A* arcs. The *N* nodes consist of either a depot node or a job node. A depot node (N_D) specifies the number of trucks at the truck depot, denoted by n_i. A job node is defined as a series of activities that should be performed for each type of job, import pickup (N_I) or export delivery (N_E). The job node includes the travel time between the container terminal and customer location, time to mount/unmount the container at the customer location, time to pack/unpack the container at the customer location, time to pick up/drop off the container at the terminal, and time waiting in queue at the terminal gate. The time it takes to complete all of these activities is called the service time (ST_i). The activity and time associated with import and export job nodes are provided in Table 3.1.

Table 3.1 Activity and time associated with import and export job nodes

Job Node *i*	**Activity and Time**
$i \in N_I$	1. Pick up import container at terminal (terminal turn time). 2. Transport container to customer (travel time between terminal and customer's location). 3. Unmount full container from truck (time to unmount container). 4. Customer unpack container (unpack time). 5. Mount empty container to truck (time to mount container).
$i \in N_E$	1. Unmount empty container from truck (time to unmount container). 2. Customer pack container (time to pack container). 3. Mount full container to truck (time to mount container). 4. Transport loaded container to terminal (travel time between customer's location and terminal). 5. Wait in queue at terminal gate (gate queuing time). 6. Drop off export container at terminal (terminal turn time).

For each job node, the attribute t_i is defined as the total time it takes to complete all of the activities prior to arriving to the destination of that job. For the import job node, the destination is the consignee's location, and thus, t_i is the combined time associated with activities 1 and 2. For the export job node, the destination is the container terminal and thus, t_i is the combined time associated with activities 1, 2, 3, 4 and 5.

Another attribute of the job nodes is the time windows, denoted by [L_i, U_i]. The interval [L_i^C, U_i^C] indicates that the activities for a job should start within this time interval at the customer's location. For the export job node, activity 1 must start within the interval $[L_i^C, U_i^C]$; thus, the job node's time window $[L_i, U_i]$ is equal to the customer location time window $[L_i^C, U_i^C]$. For the import job node, the activity 3 must start within the interval $[L_i^C, U_i^C]$. To meet this time window requirement, activity 1 must start within time interval $[L_i^C - t_i, U_i^C - t_i]$. Consequently, the import job node's time window $[L_i, U_i]$ is equal to $[L_i^C - t_i, U_i^C - t_i]$.

Table 3.2 Transfer time for all possible combination of activities at node i and node *j*

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	1. Travel time between truck depot and terminal. 2. Gate queuing time.	1. Travel time between truck depot and empty container depot. 2. Time to mount container. 3. Travel time between empty container depot and customer.
	N_I	1. Travel time between customer and empty container depot. 2. Time to unmount container. 3. Travel time between empty container depot and truck depot *j*.	1. Travel time between customer *i* and empty container depot. 2. Time to unmount container. 3. Travel time between empty container depot and terminal. 4. Gate queuing time.	*If node i customer is different from node j customer:* Travel from customer *i* to customer *j*. *Otherwise:* No activity
	N_E	1. Travel time between terminal and truck depot *j*.	No activity	1. Travel time between terminal and empty container depot. 2. Time to mount container. 3. Travel time between empty container depot to customer *j*.

The arc (i, j) represents the transfer time between the completion of node *i* activities and the commencement of node *j* activities. The transfer time on arc (i, j) depends on the combination of depot and job nodes that occur at *i* and *j*. The transfer time for all possible combinations is provided in Table 3.2. Note that there is "No activity" for the N_E and N_I combination because the truck would be at the container terminal at the completion of job N_E and thus it is at the location of where it needs to be to commence job N_I. There is also "No activity" for the N_I and N_E combination when customer *i* and *j* are the same; in this scenario, the truck would drop off the import container and then pick up the export container at the same location. The N_D to N_D combination is not considered since it is unlikely to occur in practice.

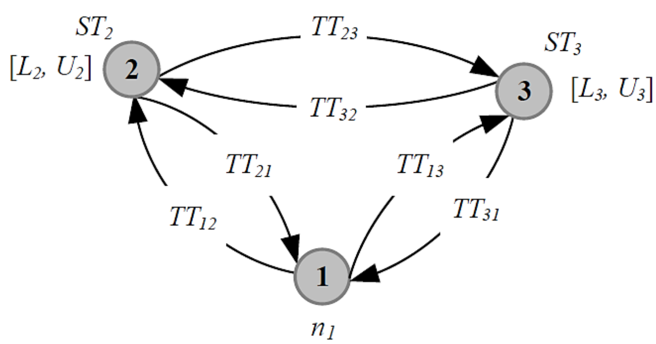


Figure 3.4 Graph representation of the drayage example illustrated in Figure 3.3.

Figure 3.4 provides the graph representation of the drayage example problem discussed previously, along with illustrative node and arc attributes. The truck depot is represented by node 1, $N_D = \{1\}$. With two trucks starting from node 1, $n_1 = 2$. The job orders for the consignee and shipper are represented by the job nodes 2 and 3, respectively; $N_J = \{2, 3\}$, $N_I = \{2\}$, $N_E = \{3\}$. Based on the activity times associated with the job orders (see Table 3.1), the service times ST_1 and ST_2 and time windows $[L_1, U_1]$ and $[L_2, U_2]$ for N_I

and N_E can be computed. The transfer times between nodes are represented by the arcs, which can be computed based on the from-to node combinations (see Table 3.2).

3.4.3 Mathematical Formulation

The mathematical formulation of the DSPTW is based on the graphical representation presented in the previous section. Its decision variables, objective function, and constraints are presented below.

$$x_{ij} = \begin{cases} 1 & \text{If arc}(i,j) \text{ is included in the solution} \\ 0 & \text{Otherwise} \end{cases}$$

$$q_{ik} = \begin{cases} 1 & \text{If customer } i \text{ books an appoinment in time period } k \\ 0 & \text{Otherwise} \end{cases}$$

s_i = Time that the first activity on node i is started.

p_i = Truck arrival time at terminal gate to start terminal related activities of node i.

$$min \sum_{i \in N_J} \sum_{j \in N_D} s_i \times x_{ij} - \sum_{i \in N_D} \sum_{j \in N_J} s_j \times x_{ij} + \sum_{i \in N_D} \sum_{j \in N_J} TT_{ij} \times x_{ij} + \sum_{i \in N_J} \sum_{j \in N_D} (ST_i + TT_{ij}) \times x_{ij} \quad (3.1)$$

$$\sum_{j \in N_J} x_{ij} \le n_i \qquad \forall i \in N_D \quad (3.2)$$

$$\sum_{i \in N_D \cup N_J} x_{ij} = \sum_{i \in N_D \cup N_J} x_{ji} = 1 \qquad \forall j \in N_J \quad (3.3)$$

$$s_i + ST_i + TT_{ij} - (1 - x_{ij}) \times M \le s_j \qquad \forall i,j \in N_J \quad (3.4)$$

$$TT_{ij} - (1 - x_{ij}) \times M \le s_j \qquad \forall i \in N_D, \forall j \in N_J \quad (3.5)$$

$$L_i \le s_i \le U_i \qquad \forall i \in N_J \quad (3.6)$$

$$p_i = s_i \qquad \forall i \in N_I \qquad (3.7)$$

$$p_i = s_i + t_i \qquad \forall i \in N_E \qquad (3.8)$$

$$p_i - M \times (1 - q_{ik}) \le U_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_J \qquad (3.9)$$

$$p_i + M \times (1 - q_{ik}) \ge L_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_J \qquad (3.10)$$

$$\sum_{k \in T} q_{ik} = 1 \qquad \forall i \in N_J \qquad (3.11)$$

$$\sum_{i \in N_J} q_{ik} \le Q_k \qquad \forall k \in T \qquad (3.12)$$

Equation (3.1) is the objective function which seeks to minimize the drayage operation time. The first term of the objective function is the start times of the trucks' last jobs prior to returning to the truck depot. The second term is the start times of the trucks' first jobs after leaving the truck depot. The difference between these two terms represents the operation time of all trucks between their first and last jobs. The third term is the transfer time between the truck depot and the location of trucks' first jobs. The fourth term is the service time of the trucks' last jobs and transfer time between the location of these jobs and the nearest truck depot. Constraint (3.2) is the capacity constraint for truck depots which ensures that the number of routes started from each truck depot is less than or equal to the initial number of trucks at that depot. Constraint (3.3) states that each job node should be visited exactly once. Constraints (3.4) and (3.5) enforce the time relationship of consecutive nodes along a route. Constraint (3.6) restricts the start time of job nodes to their time windows. Constraints (3.7) and (3.8) compute the arrival time of the truck to the terminal gate. Constraints (3.9) and (3.10) determine the time period at which a truck should book an appointment based on the truck arrival time at the terminal gate (computed by constraints (3.7) and (3.8)). Constraint (3.11) ensures that only one appointment is booked for each job node. Constraint (3.12) limits the number booked appointments in each time period to the specified quota for that time period (i.e. the time period capacity cannot be exceeded).

3.5 SOLUTION METHODOLOGY

The proposed mathematical model is NP-hard since it is an extension of the NP-hard problem m-TSPTW and meta-heuristics are widely used to solve similar problems.

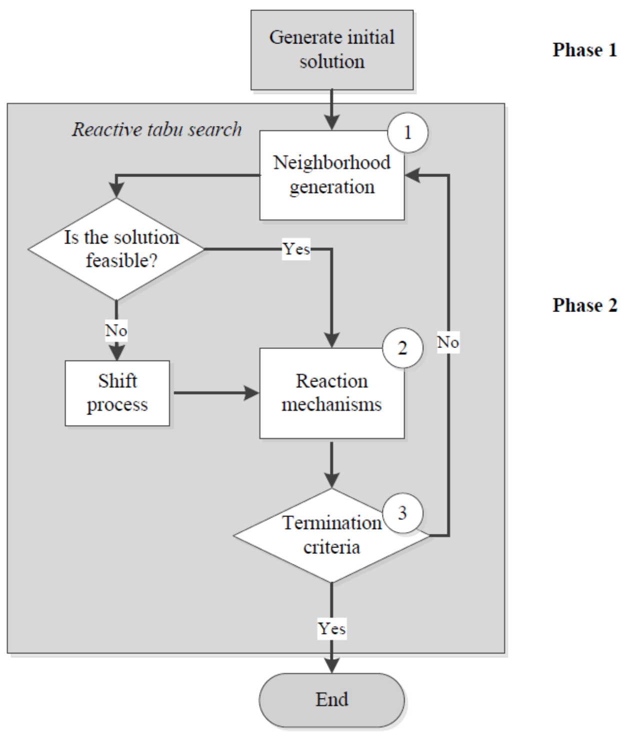


Figure 3.5 Flowchart of developed solution methodology

The proposed solution methodology in this work is based on the RTS algorithm (Battiti and Tecchiolli, 1994). While a number of meta-heuristics could be used to solve the proposed model, RTS is used in this study because it has been found to be successful in solving drayage problems (Zhang et al., 2009, 2011, 2015), as well as vehicle routing problems (Chiang and Russell, 1997; Osman and Wassan, 2002; Wassan et al., 2008). The solution method consists of two phases. Phase 1 generates an initial solution via a greedy heuristic and phase 2 seeks to obtain the optimal solution via the RTS. Figure 3.5 provides an overview of the developed solution methodology.

3.5.1 Initial Solution Generation Procedure

Phase 1 uses a greedy heuristic to generate an initial solution. The heuristic involves adding job nodes one at a time to a feasible route that yields the lowest cost route from a depot node by using objective function. Each time a route is constructed from a depot node the number of trucks at that depot is decreased by one. The procedure continues to add the lowest-cost unassigned job node until no job can be further added to this route while satisfying constraints (3.6), (3.11), and (3.12), as well as (3.13) through (3.18). At this point, the truck should return to one of truck depots and the heuristic selects the depot nearest to its last job node. This process is repeated until all job nodes are assigned to routes or no more route can be created. If there are trucks that are not used in the solution, their corresponding depot nodes are inserted at the end and empty routes are constructed. If the number of trucks or appointment quotas is not sufficient, then the initial solution could be infeasible. In these cases, unassigned job nodes are kept in a set and the RTS will start with an infeasible initial solution.

Figure 3.6 provides the pseudo codes for the greedy heuristic, which uses the following variables and definitions.

$$s_j = max\left\{TT_{ij}, L_j\right\},\ \forall i \in N_D, \forall j \in N_J \tag{3.13}$$

$$s_j = max\left\{s_i + TT_{ij} + ST_i, L_j\right\},\ \forall i, j \in N_J \tag{3.14}$$

$$k = arg \min_{\substack{k \in T \text{ with} \\ \text{nonzero remaining capacity} \\ \text{and } p_i >= L_k^T}} \left\{L_k^T\right\} \tag{3.15}$$

$$p_j = max\ \left\{L_k^T, p_j\right\} \tag{3.16}$$

$$j = arg \min_{j \in UA} \left\{ TT_{ij} \right\},\ \forall i \in N_D, \forall j \in N_J \tag{3.17}$$

$$j = arg \min_{j \in UA} \left\{ s_j \right\},\ \forall i, j \in N_J \tag{3.18}$$

where *UA* is the unassinged job node set and *i* is the from node and *j* is the to node.

In Figure 3.6, the outer until loop generates routes from a depot node, and the inner until loop adds job nodes to this route until no more job nodes can be further added to this route. A solution *S* is represented by a set of truck routes, $S = \{R_1, R_2, \ldots, R_v\}$ with *v* being the total number of trucks in all truck depots. For the problem shown in Figure 3.4, the solution is represented by $S = \{R_1, R_2\}$ and a possible solution is $R_1 = \{1, 2, 3\}$ and $R_2 = \{1\}$. The values in the set R_1 indicate that a truck will depart from the truck depot (node 1) and then go to job nodes 2 and 3. R_2 consists only of node 1 which implies that the second truck will remain at the depot node and thus this is an empty route.

until (all job nodes are assigned to routes or no more route can be created)
for all $i \in N_D$ with nonzero capacity
for all $j \in UA$
Calculate s_j using (13)
if $j \in N_I$
Calculate p_j using (7)
else
Calculate p_j using (8)
end
Find the time period k that an appointment can be booked using (15)
Recalculate p_j using (16)
if $j \in N_I$
Recalculate s_j using (7)
else
Recalculate s_j using (8)
end
end
Find the lowest-cost job node using (6) and (17)
end
Find the lowest-cost job node
Reduce trucks number in depot i and time period k's capacity by one
$i \leftarrow j$
until no more insertion is valid
for all $j \in UA$
Calculate s_j using (14)
if $j \in N_I$
Calculate p_j using (7)
else
Calculate p_j using (8)
end
Find the time period k that an appointment can be booked using (15)
Recalculate p_j using (16)
if $j \in N_I$
Recalculate s_j using (7)
else
Recalculate s_j using (8)
end
end
Find the lowest-cost job node using (6) and (18)
Reduce time period k's capacity by one
end
end

Figure 3.6 Initial solution's algorithm

3.5.2 Reactive Tabu Search

Tabu search (TS) is a memory based metaheuristic which uses neighborhood search and prohibition-based techniques. During the exploration process, a collection of

.

solutions are created by a set of moves that transforms one solution into another. A collection of adjacent solutions that can be reached from a solution is called a neighborhood. TS prevents cycling back to the previously visited solutions during the search by recording the recent history of moves as forbidden moves in a short-term memory list, called tabu list. The forbidden moves are kept in the tabu list for a period of time, known as tabu tenure. However, tabu restriction is not strict, it can be overridden when a tabu move results in a solution better than all visited solutions. Reactive search was introduced by Battiti et al. (1994) to improve TS by using the history of already visited solutions to guide the search. Tabu tenure is changed dynamically in RTS by tracking the number of repeated solutions. Moreover, an escape mechanism is performed when the search is trapped in the solution space characterized as a "chaotic attractor basin". The following sections provide specific details regarding this study's implementation of RTS components.

3.5.2.1 Neighborhood Generation

RTS explores the solution space by moving from a solution *S* to an adjacent solution *S'*. That is, through the neighborhood generation mechanism (step 1 of phase 2 shown in Figure 3.5) the neighborhood of the current solution *N(S)* is generated at each iteration; the number of neighborhood solutions to be generated is equal to the specified maximum neighborhood size parameter. Then, the best solution in the neighborhood is selected, even if it is worse than the current solution, as the new current solution, and the procedure is repeated. The neighborhood generation mechanism used in this paper is the *λ-interchange* mechanism introduced by Osman (1993) which exchanges a subset of job nodes between routes to generate a neighboring solution. We implemented λ-*interchange* mechanism with λ = 1 which works as follows.

Let $S = \{R_1, R_2, \ldots, R_v\}$ be a solution. First, two routes are selected from the solution S randomly, say R_p and R_q. Then two subsets of nodes (S_p and S_q) are chosen from the nodes in R_p and R_q: $S_p \subseteq R_p$ and $S_q \subseteq R_q$. The *1-interchange* mechanism exchanges a subset of S_p of size $|S_p| \leq 1$ from R_p with a subset of S_q of size $|S_q| \leq 1$ from R_q and thus generates two new routes, R'_p and R'_q, and a new solution S'. This mechanism invokes two processes to generate neighboring solutions, *shift* and *interchange* processes:

- A *shift* process is represented by (1,0) or (0,1) operators. These operators move one job node from a route to another route. For instance, the (1,0) operator removes one job node from route R_p and adds it to route R_q.
- An *interchange* process is represented by the (1,1) operator which exchanges one job node between routes R_p and R_q.

Note that with the *interchange* process the length of the route is not changed, whereas with the *shift* process the (0,1)/(1,0) operator will increase/decrease the length of route R_p and decrease/increase the length of route R_q by one. Furthermore, for the *interchange* process one job node is selected from each of the two randomly selected routes, and similarly for the *shift* process one job node is selected from one of the two selected routes. For both the *shift* and *interchange* processes, the selected job nodes are inserted in the best position on the other routes.

To improve the quality of the solution, this study also implemented a mechanism called *Local-shift* introduced by Wassan et al. (2008). This mechanism is used after the λ -*interchange* mechanism, and it is applied to the routes which were altered by the λ-

interchange mechanism. The *Local-shift* relocates a job node to a different position within the route, if such a move improves the solution. To generate adjacent solutions, all three neighborhood generation mechanisms are used at each iteration. Each time that a new solution is obtained, the tabu status of the corresponding moves and the feasibility of the solution are checked and the solution is evaluated using objective function. If the algorithm starts with an infeasible initial solution, then at each iteration when the new solution is found (after the neighborhood generation step) the shift process will then be used to check the feasibility of moving some or all of the unassigned jobs to the new solution. The maximum neighborhood size used for experiment 1 to 8 is 200, experiment 9 to 15 is 1000, and experiment 16 to 27 is 2000.

3.5.2.2 Reaction Mechanisms

The history of visited solutions can affect the search path in RTS algorithm (step 2 of phase 2 shown in Figure 3.5). RTS tracks the frequency of revisiting solutions to adjust the search trajectory with two reaction mechanisms. Figure 3.7 provides the algorithmic steps involved in the reaction mechanism. These mechanisms are briefly explained below.

1. The tabu tenure (*tt*) is dynamically controlled. If a solution is repeated within a predefined number of iterations (*CYCLE_MAX*), then it means that the algorithm is falling into a cycle. In this case, the tabu tenure is increased by a predetermined factor *INC* where *INC* > 1 (step 3 in Figure 3.7). Moreover, a moving average (*movingAverage*) of detected cycles is calculated during the search procedure. If number of iterations passed from last change of tabu tenure is more than this moving average, then the tabu tenure is decreased by a predetermined factor *DEC* where 0

< *DEC* < 1 (step 4 shown in Figure 3.7). Each time that the tabu tenure is updated it is rounded up to the next integer.

2. If a solution is repeated more than *REP* times (*REP* is a predefined parameter), then that solution is considered as an often-repeated solution (step 2 in Figure 3.7). If the number of often-repeated solutions is more than *CHAOS* (*CHAOS* is a predefined parameter), then it can be concluded that the search is confined to an attractor basin. In this case, RTS will use the escape mechanism to get out of the basin. The escape mechanism clears the tabu list and performs successive random moves. This mechanism will change the makeup of the solution and move the search into a different region of the solution space.

3.5.2.3 Termination Criteria

The developed algorithm is terminated after a certain number of iterations (step 3 of phase 2 shown in Figure 3.5) which is defined based on the size of the problem. Our algorithm is terminated after performing $50\times n$ iterations where n is total number of nodes.

3.5.2.4 RTS components

Tabu list: In this study, the data structure used to store the tabu list is called *TABL*, which is adopted from work of Chiang and Russell (1997). *TABL* is a matrix with n rows and v columns (n is the number of job nodes and v is the number of routes). The matrix *TABL* is initialized with high negative values. *TABL* (i,p) records the iteration number at which job node i was removed from route R_p. Suppose at iteration k, job node i is a candidate to move to the route R_p. This move is classified as tabu if:

$$k - TABL(i, p) < tt \tag{3.19}$$

Step 0: Initialization of reaction mechanisms parameter.
repeat = 0 (Number of iterations that a solution has been visited)
chaotic = 0 (Number of often-repeated solutions)
movingAverage = 0 (Moving average of the iteration intervals between detected cycle)
changeInterval = 0 (Number of iterations passed after last change in tabu tenure value)
revisitInterval = 0 (Number of iteration between current and previous occurrence of a solution)
tt = 5: tabu tenure value
REP=3
CHAOS= 6
INC=1.1
DEC=0.9
CYCLE_MAX = 50

Step 1:
Search for the current solution (*S*) in the hash matrix
if *S* found in the hash matrix
revisitInterval = number of iteration between current and previous occurrence of *S*
repeat = *repeat* + 1
else
Add *S* to hash matrix
Go to *Step 4*
end

Step 2:
if *repeat >REP*
repeat = 0
chaotic = *chaotic* + 1
else
Go to *Step 3*
end
if *chaotic* > *CHAOS*
chaotic = 0
Execute escape mechanism
Stop
else
Go to *Step 3*
end

Step 3:
if *revisitInterval* < *CYCLE_MAX*
tt = *tt* × *INC*
changeInterval = 0
movingAverage = 0.1 × *revisitInterval* + 0.9 × *movingAverage*
Stop
else
Go to *Step 4*
end

Step 4:
if *changeInterval* > *movingAverage*
tt = *tt* × *DEC*
changeInterval = 0
Stop
else
changeInterval = *changeInterval* + 1
Stop
end

Figure 3.7 Reaction mechanism.

Hashing function: RTS requires a method to compare the obtained solution with previously visited solutions and determine if a solution has been visited or not, and if yes, how long ago. Considering the number and size of the solutions, storing all characteristics of visited solutions and comparing a new solution with all visited solutions is computationally expensive and memory-consuming. To identify previously visited solutions, representative information of visited solutions can be used as a solution identity. In this study, a solution identity is its hash value calculated from the following hashing function proposed by Woodruff and Zemel (1993):

$$\text{Hash value} = \left[\sum_{i=1}^{n} z(x_i)z(x_{i+1})\right] \text{mod} \left[\text{MAXINT} + 1\right] \tag{3.20}$$

where:

n = the cardinality of set X,

X = a solution vector, where $x_i \in X$ for i = 1..n (since length of vector X is n, x_{n+1} is not defined. So, x_{n+1} will be replaced by x_1 when i=n),

Z = a vector of pre-generated values between 1 … m, where $z_i \in Z$ for i = 1..n (m is a big number), and

MAXINT = the maximum integer that can be represented by the computer.

Hash values associated with each solution are stored in a matrix called hash matrix. Each row of the hash matrix is related to a solution which stores the solution's hash value along with the number of repeated visits and the last iteration that visit occurred. Each time a new solution is obtained its hash value is searched in the hash matrix. If it is not found, then this solution is added to the hash matrix. Otherwise, the number of repeated visits is increased by one and the iteration of the last visit is updated to the current iteration.

3.6 NUMERICAL ANALYSIS

To demonstrate the feasibility of the developed model and solution methodology, they are tested on randomly generated instances with real life characteristics. Instances are generated on a hypothetical network shown in Figure 3.8 with one container terminal, one empty container depot and two truck depots. The size of the network is chosen to be sufficiently large; in particular, the travel time along the edges of the network is chosen to be 3 hours. The container terminal and the empty container depot are 10 minutes apart. The customer locations are generated randomly within the network.

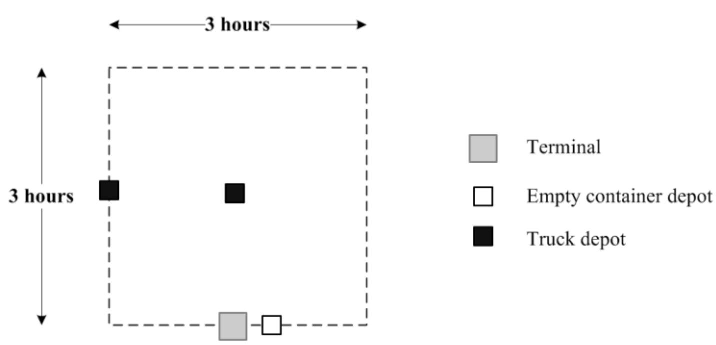


Figure 3.8 Illustration of hypothetical network.

The time to mount/unmount the container is assumed to be 5 minutes (Chung et al., 2007). Packing/unpacking times are assumed to be uniformly distributed with a minimum of 5 minutes and a maximum of 60 minutes, U(5, 60) (Zhang et al., 2010). Lower bound of time windows are assumed to be uniformly distributed in the range of 0 (8:00 A.M.) to

240 (12:00 P.M.) and the upper bound is calculated according to the width of the time window. The width of the time window is assumed to be 240 minutes. Chen et al. (2013) considered five target levels for the average gate queueing time: 2, 5, 10, 15, and 20 minutes. In this study, a queueing time of 10 minutes is assumed, except for those experiments shown in Table 3.6. The container terminal is assumed to operate 10 hours each day and there are a total of 10 time periods (i.e. $T = 10$). Appointment quotas in each time period are assumed to be uniformly distributed with a minimum of 0 and a maximum of the number of job nodes divided by 3, U(0, number of job nodes/3).

The developed mathematical formulation is a mixed-integer quadratic programming model (MIQP). To obtain the exact solutions to validate our model and solution methodology, we used the commercial solver CPLEX. Note that the current version of CPLEX, 12.6.1, is capable of solving MIQP. The solution methodology, RTS, was coded in MATLAB R2012b. The experiments were conducted on a desktop computer with a 3.40 GHz processor and 16 GB of RAM. This study used the RTS parameter values suggested by Osman and Wassan (2002) as a starting point. These parameters were then systematically adjusted and fine-tuned such that the RTS gives the same optimal solution as CPLEX for small-sized and some medium-sized problems.

The results for small to medium-sized problems are provided in Table 3.3. The first column shows the experiment number. The second column shows the problem size in terms of number of job nodes. The third and fourth columns show the objective function values and computation time of CPLEX, respectively.

Table 3.3 Comparison of RTS performance against CPLEX for small and medium-sized problems

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Experiment No.	**Problem size**	**CPLEX**		**Solution method**			
				Initial feasible solution	**RTS**		
		Objective value	**Time (s)**	**Objective value**	**Objective value**	**Time (s)**	**Gap[1] (%)**
1	2	517	0.01	517	517	2.5	0
2	3	856	0.01	899	856	4.23	0
3	4	871	0.12	1104	871	5.98	0
4	5	1112	0.13	1485	1112	6.818	0
5	6	1126	0.30	1303	1126	9.39	0
6	7	1253	0.36	1469	1253	11.67	0
7	8	1660	0.47	2143	1660	12.82	0
8	9	1669	0.78	2078	1669	16.87	0
9	10	1613	1.64	1960	1613	100.65	0
10	11	1755	2.00	2349	1755	119.82	0
11	12	1979	6.74	2711	1979	124.03	0
12	13	2097	26.21	2375	2097	132.90	0
13	14	2447	30.17	2625	2447	150.35	0
14	15	2452	32.75	2823	2452	153.55	0
15	20	3421	149.76	3665	3421	168.14	0
16	25	4034	2940.05	5013	4034	301.45	0
17	30	5415	12175.46	7273	5415	379.45	0
18	35	6076	20292.51	7282	6152	483.45	1.25
19	40	6821	91433.76	7518	7075	513.01	3.72

[1]Gap = 100 × (RTS solution - CPLEX solution)/CPLEX solution.

The results obtained from the developed solution methodology (RTS) are reported in the fifth, sixth and seventh columns. The fifth column shows the objective function value of the initial feasible solution. The sixth column shows the RTS objective function value, and the seventh column shows the RTS computation time. The last column shows the gap between the CPLEX and RTS solutions. As indicated by the gap values, RTS yields the same optimal solutions as CPLEX for 17 experiments out of 19 small and medium-sized problems. RTS was not able to produce the same optimal solutions for experiments 18 and 19 which had 35 and 40 job nodes. However, RTS was able to obtain nearly the same solution (gap of less than 3.72%) in a fraction of the computation time (8.55 minutes for RTS vs. 25.39 hours for CPLEX). It should be noted that the reported computation time for RTS is based on its implementation in the MATLAB environment. It is expected that the computation time will be much less if the RTS algorithm is implemented in a lower-level programming language such as C++.

It can be seen in Column 4 of Table 3.3 that the computation time of CPLEX increases significantly as the problem size increases. As noted, experiment 19 took CPLEX over 25 hours to obtain the optimal solution. For this reason, CPLEX runs were limited to 4 hours for large-sized problems, shown in Table 3.4. The first column of Table 3.4 shows the experiment number. The second column shows the problem size in terms of number of job nodes. The CPLEX incumbent solution at the end of the 4-hour run is reported in the third column. An "N/A" in the third column indicates that CPLEX was not able to obtain a solution. The fourth column shows the objective function value of the initial feasible solution. The fifth column shows the RTS objective function value, and the sixth column shows the RTS computation time. The last column shows the gap between the CPLEX and RTS solutions. As indicated by the negative gap values, the RTS solutions for experiments 20 to 24 were lower (better) than the CPLEX solutions. It should be noted that a reason why CPLEX did not perform as well is due to the time limit. For very large problems (experiments 25 to 27), CPLEX could not find a solution due to either time limit or memory limit. The results in Table 3.4 verified that the developed integrated model is solvable by RTS within reasonable time for operational problems. The largest problem (experiment 27) with 200 job nodes took RTS less than 34 minutes to obtain the solution; as noted, CPLEX was unable to obtain a solution for this problem due to time or memory limit.

The sensitivity of the drayage operation time to various problem characteristics (e.g. appointment quotas in each time period, gate queuing time, and truck depot locations) was analyzed via a series of experiments.

Table 3.4 Comparison of RTS performance against CPLEX for large-sized problems

(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
Experiment No.	**Problem size**	**CPLEX**	**Solution method**			**Gap[1] (%)**
			Initial feasible solution	**RTS**		
		Objective value	**Objective value**	**Objective value**	**Time (s)**	
20	45	7932	8602	7296	535.15	-8.02
21	60	11000	11849	10270	765.92	-6.64
22	80	16010	16925	15520	895.37	-3.06
23	100	18927	19279	17927	1024.98	-5.28
24	120	22943	23277	21121	1375.69	-7.94
25	150	N/A	31200	28819	1699.80	N/A
26	180	N/A	33744	30804	1874.25	N/A
27	200	N/A	37910	36143	2003.24	N/A

[1]Gap = 100 × (RTS solution - CPLEX solution)/CPLEX solution

The effect of appointment quotas on the objective function values are summarized in Table 3.5. The test problems for these experiments consist of problems with 50, 60 and 70 job nodes. The first column in the Table 3.5 shows the experiment number, and the second column shows the problem size. The third column shows the set of appointment quotas. The forth column reports results obtained from RTS which are the set of booked appointments and the last column reports the objective function values. The solutions for experiments 28, 37 and 46 (will be referred to as base experiments) indicated that the number of booked appointments in the sixth and tenth time periods is equal to the set quotas, and thus, these quotas could potentially prevent the drayage firms from improving their operation time. To test how sensitive the objective function values are to these quotas, 8 different variations of appointments quotas were tested, as outlined below.

Quota variations from base experiment
1: Increase quota by 1 in the sixth time period
2: Increase quota by 2 in the sixth time period
3: Decrease quota by 1 in the sixth time period
4: Decrease quota by 2 in the sixth time period
5: Increase quota by 1 in the sixth and tenth time periods
6: Increase quota by 2 in the sixth and tenth time periods
7: Decrease quota by 1 in the sixth and tenth time periods
8: Decrease quota by 2 in the sixth and tenth time periods

Experiments 29 to 36 are the variations of base experiment 28. Experiments 38 to 45 are the variations of base experiment 37, and experiments 47 to 54 are the variations of base experiment 46.

From the sensitivity analysis results (Table 3.5), higher appointment quotas via variations 1, 2, 5, or 6 led to a reduction in the objective function values and thus more efficient drayage schedules. For example, for variation 6, compared to the base experiments the objective function value for experiment 34 decreased by 242 minutes (2.40%), objective function value for experiment 43 decreased by 285 minutes (2.46%), and objective function value for experiment 52 decreased by 395 minutes (2.72%). Conversely, lower appointment quotas led to an increase in the objective function value and thus less efficient drayage schedules. For example, for variation 8, compared to the base experiments the objective function value for experiment 36 increased by 208 minutes (2.06%), objective function value for experiment 45 increased by 421 (3.64%), and objective function value for experiment 54 increased by 354 minutes (2.44%).

Table 3.5 Effect of appointment quotas on drayage operation time

Experiment No.	Problem size	Set of appointment quotas	Set of booked appointments	Objective value
28		(10,10,10,10,10,10,10,10,10,10)	(0,2,9,2,8,10,6,1,2,10)	10092
29		(10,10,10,10,10,11,10,10,10,10)	(0,6,6,2,5,11,7,2,1,10)	9984
30		(10,10,10,10,10,12,10,10,10,10)	(0,6,2,7,6,12,4,3,2,8)	9899
31		(10,10,10,10,10,9,10,10,10,10)	(0,6,5,1,7,9,6,3,3,10)	10161
32	50	(10,10,10,10,10,8,10,10,10,10)	(0,6,3,4,9,8,5,2,3,10)	10220
33		(10,10,10,10,10,11,10,10,10,11)	(0,4,7,2,4,11,5,3,4,10)	9955
34		(10,10,10,10,10,12,10,10,10,12)	(0,5,6,2,4,12,3,3,5,10)	9850
35		(10,10,10,10,10,9,10,10,10,9)	(0,8,2,4,10,9,3,5,0,9)	10201
36		(10,10,10,10,10,8,10,10,10,8)	(0,4,3,5,9,8,6,5,2,8)	10300
37		(10,10,10,10,10,10,10,10,10,10)	(0,6,6,2,9,10,10,4,3,10)	11574
38		(10,10,10,10,10,11,10,10,10,10)	(0,6,6,2,8,11,9,4,4,10)	11445
39		(10,10,10,10,10,12,10,10,10,10)	(0,6,6,3,8,12,8,4,3,10)	11309
40		(10,10,10,10,10,9,10,10,10,10)	(0,7,4,5,10,9,7,5,3,10)	11658
41	60	(10,10,10,10,10,8,10,10,10,10)	(0,7,5,5,8,8,10,5,3,9)	11853
42		(10,10,10,10,10,11,10,10,10,11)	(0,5,7,6,5,11,4,6,5,11)	11365
43		(10,10,10,10,10,12,10,10,10,12)	(0,5,5,7,6,12,5,7,2,11)	11289
44		(10,10,10,10,10,9,10,10,10,9)	(0,2,9,4,8,9,10,4,5,9)	11699
45		(10,10,10,10,10,8,10,10,10,8)	(0,4,6,5,8,8,10,5,6,8)	11995
46		(10,10,10,10,10,10,10,10,10,10)	(0,10,5,8,10,10,5,5,7,10)	14500
47		(10,10,10,10,10,11,10,10,10,10)	(0,6,9,6,10,11,9,7,4,8)	14456
48		(10,10,10,10,10,12,10,10,10,10)	(0,10,5,6,8,12,6,5,8,10)	14211
49		(10,10,10,10,10,9,10,10,10,10)	(0,7,9,6,10,9,9,6,4,10)	14551
50	70	(10,10,10,10,10,8,10,10,10,10)	(0,7,8,7,10,8,10,6,4,10)	14701
51		(10,10,10,10,10,11,10,10,10,11)	(0,8,7,7,9,11,6,8,3,11)	14441
52		(10,10,10,10,10,12,10,10,10,12)	(0,10,6,4,10,12,9,3,4,12)	14105
53		(10,10,10,10,10,9,10,10,10,9)	(0,6,10,6,10,9,5,8,8,8)	14637
54		(10,10,10,10,10,8,10,10,10,8)	(0,10,7,6,10,8,10,6,5,8)	14854

Comparing the results of those experiments with 50, 60, and 70 job nodes (see column 2 of Table 3.5), it was expected that the percentage of change in the objective function value will increase with problem size; however, that was not the case. For example, in experiment 45 (variation 8) with 60 job nodes, the objective function value increased by 421 minutes (3.64%), whereas in experiment 54 (variation 8) with 70 job nodes the objective function value increased by 354 minutes (2.44%). According to the results, for a given increase or decrease in quota, there appears to be no correlation between problem size and percentage of change in objective function value.

Figure 3.9a illustrates the relationship between the objective function value and change in appointment quotas (variations 1 to 4) for three problem size (50, 60, and 70 job nodes). Figures 3.9b, 3.9c, and 3.9d show the same results for each problem size in a finer scale. The shown graphs indicate that as the appointment quotas are increased, the objective function value will decrease; however, this trend is not linear. These results suggest that drayage operation time is affected not just by the appointment quotas, but also perhaps by other operational constraints such as time windows at customers' locations, travel time, and location of empty container depot and truck depot. Figures 3.9b, 3.9c and 3.9d also shows the results of variations 5 and 7, denoted as asterisks. This is intended to compare the effect of increasing or decreasing two appointment quotas in one time period (variations 2 and 4) vs. increasing or decreasing one appointment quota in two different time periods (variations 5 and 7). It can be concluded that decreasing two appointment quotas in one time period has more negative effect on the objective function value than decreasing one appointment quota in two different time periods. Conversely, increasing two appointment quotas in one time period has more positive effect on the objective function value than increasing one appointment quota in two different time periods. These results suggest that in increasing or decreasing the appointment quotas, not only are their values important but also how they are distributed among the time periods.

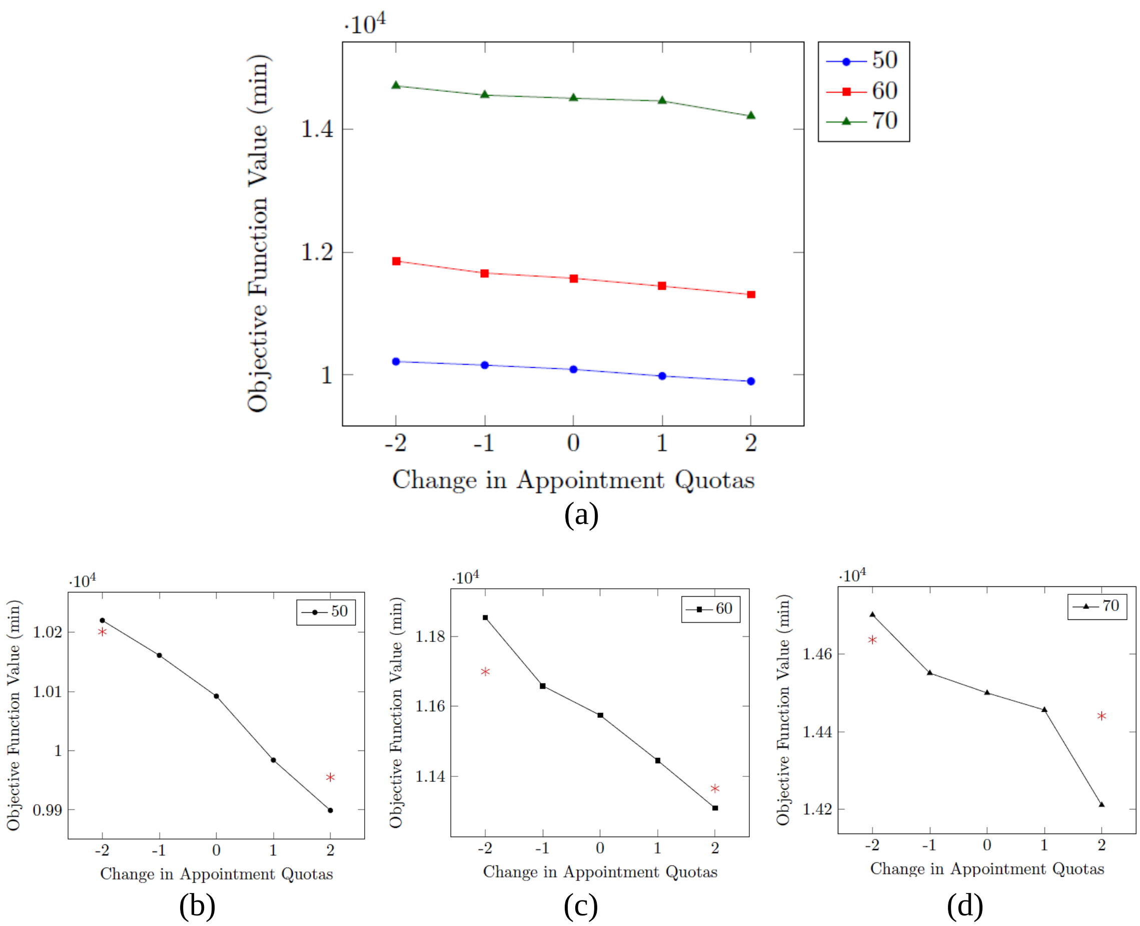


Figure 3.9 Effect of change in number of appointment quotas on objective function value

To test the effect of gate queuing time on drayage operation time, two different queuing times were used: 2 and 20 minutes; these numbers represent an ideal gate queuing time with the truck appointment system implemented and a typical gate queuing time. The test problems for these experiments consist of problems with 50, 100, 150 and 200 job nodes (50% import and 50% export). The results of this experiment are reported in Table

3.6. The first column shows the experiment number, and the second column shows the problem size. The third and fourth columns report the objective function values obtained from RTS for 20 and 2 minutes gate queuing time, respectively. The results indicate a reduction in gate queueing time from 20 to 2 minutes will reduce the drayage operation time. The reduction in objective function value ranges from 3.27 hours (2.19%) (in experiment 55) to 28.03 hours (4.63%) (in experiment 58). The results correspond to intuition that shorter gate queuing time will lead to a more efficient drayage operation. They highlight the fact that if terminal operators schedule trucks at the terminal in a manner that maximizes the effectiveness of appointment systems, then the negative effect of the appointment system on drayage firm will diminish as a result of reducing truck queuing/idling time. In addition, these findings can help terminal operators in setting up the appointment system by giving them insight into the effect of different queuing time on drayage firms.

Table 3.6 Effect of gate queuing time on drayage operation time

Experiment No.	**Problem size**	**Gate queuing times**	
		20 (min)	**2 (min)**
55	50	8955	8759
56	100	19327	18329
57	150	26078	24961
58	200	36309	34627

The final set of experiments was conducted to investigate the impact of truck depot location on drayage operation time. For this experiment, a network with only one truck depot is used. Locations A, B and C in Figure 3.10a are three candidate locations for the truck depot. Locations B and C are closer to the terminal than location A, and they both have the same travel time to the terminal, but location C is 20 minutes closer to the empty container depot. The test problems for this experiment consist of 50 import and 50 export job nodes (at random locations). Figure 3.9b shows the relationship between the objective function value and the location of truck depot. It can be seen in the graph that changing the truck depot location from A to C reduced the objective function value by about 6.13%. This finding suggests that a truck depot closer to both the terminal and empty container depot will benefit the drayage operations. This result makes sense since all routes must begin from the truck depot to either the empty container depot (to pick up an empty container) or the terminal (to pick up a full container) and end with the truck traveling from either the empty container depot (after dropping off an empty container) or the terminal (after dropping off a full container) to the truck depot. It can be generalized from these results that the location of the truck depot has an effect on drayage operation time; the closer it is to the terminal and empty container depot the better, regardless of where customers are located in the network.

3.7 CONCLUSION

This paper addressed the challenge posed to drayage firms of having to make appointments at terminals in advance. In this emerging practice, drayage firms need to make scheduling decisions while complying with the terminal-specified truck appointment system. To address this problem, a mixed-integer programming model was developed to solve the empty container allocation problem, vehicle routing problem and appointment booking problem in an integrated manner. A reactive tabu search algorithm (RTS) combined with a greedy algorithm was developed to solve the integrated optimization model. To demonstrate the feasibility of the developed model and solution methodology, they are tested on a hypothetical network via a series of experiments with real life characteristics. The RTS solutions demonstrated that the developed integrated model is capable of finding the optimal solutions and is solvable within reasonable time for an operational problem.

The developed integrated model allowed for the evaluation of the effect of the truck appointment system on drayage operations. Experimental results indicated that 1) the appointment quota per time period set by the terminal operator has a significant effect on drayage operation time (the objective function value decreases as the quota increases, but the trend is not linear), 2) for a given change in appointment quota, there is no correlation between problem size and percentage of change in objective function value, 3) the drayage firms could benefit considerably with an efficient truck appointment system that minimizes gate queuing/idling time, and 4) truck depots should be sited close to the terminal and empty container depot.

This study has a few limitations that need to be taken in account when interpreting the aforementioned results. First, the drayage problem was treated as a static and deterministic problem, and hence, it did not account for traffic congestion, accidents, and other unexpected delays that would result in trucks potentially missing appointments. Second, it did not consider cases where trucks need to be rerouted due to accidents. Third, this study assumed that the truck turn time at the terminal is deterministic. Lastly, it should be noted that these results are based on a hypothetical network with a single drayage firm. Future research in this area could seek to improve on the aforementioned four limitations, as well as consider a centralized approach to optimize the truck appointment system for both the terminal operator and drayage firms. In addition, future research could seek to use more intricate truck appointment system features as outlined in the work by Huynh et al. (2016).

ACKNOWLEDGEMENT

This paper is based upon work supported by the National Science Foundation under Grant No. 1100227.

CHAPTER 4: ASSESSMENT OF U.S. CHASSIS SUPPLY MODELS ON DRAYAGE PRODUCTIVITY AND AIR EMISSIONS[3]

[3] Shiri, S. and Huynh, N., 2017. Assessment of US chassis supply models on drayage productivity and air emissions. Transportation Research Part D: Transport and Environment.

ABSTRACT

A new drayage scheduling model is developed to assess the effectiveness of different U.S. chassis supply models. It extends previous drayage models by incorporating these features: (1) treating tractor, container, and chassis as separate resources which are provided in different locations, (2) ensuring that container and chassis are of the same size and type, and (3) considering the possibility that drayage companies can subcontract the work to independent owner-operators whose trucks will originate from and terminate at different locations. The resulting model is a mixed-integer quadratic programming model that solves the scheduling of tractor, loaded container, empty container and chassis in drayage operation in an integrated manner. The mathematical model is an extension of the multiple traveling salesman problem with time windows (m-TSPTW). To efficiently solve the developed model, a reactive tabu search (RTS) algorithm combined with an insertion heuristic is developed. The model and algorithm are used to evaluate the effectiveness of different chassis supply models currently in use in the U.S. The results indicated that among the U.S. chassis models the co-op pool, terminal pool and rental pool with chassis yard inside the terminal yield the lowest drayage operation time, percentage of empty movements, and air emissions.

4.1 INTRODUCTION

International ocean chassis plays a critical function in the pre- and end-haulage of intermodal container transport performed by truck; these segments are referred to as drayage. A chassis is a wheeled structure that supports containers when they are transported by trucks. Container chassis in the U.S. have a fixed size to support a specific container size; that is, a 20-ft container needs to be transported with a 20-ft chassis and a 40-ft container needs to be transported with a 40-ft chassis. In the U.S., the ratio of 20-ft to 40-ft to 45-ft chassis is 25:65:10 (NCFRP Report 20); this ratio suggests that the majority of containers and chassis used in the U.S. are 40-ft long. In addition to standard chassis, there are specialty chassis. For example, refrigerated containers require chassis that are equipped with a generator to provide electric power to the containers.

Ocean container chassis logistics is a bottleneck and source of delay for drayage operations (NCFRP Report 11) as well as terminal operations (Bonney and Mongelluzzo, 2014). The reasons are: (1) delivering container and chassis to two different locations increases the travel and waiting time, (2) there is an insufficient number of chassis available to support drayage operations during the peak periods, and (3) truckers often encounter out-of-service chassis which requires them to search for a serviceable one and/or requires them to wait for the chassis to be repaired.

Historically, chassis are owned and operated by ocean carriers and stored within the terminals in the U.S. This model is unlike most in other parts of the world such as Europe where chassis are owned by trucking companies (Zumerchik et al., 2010). Recently, many ocean carriers seek to exit the chassis supply business in the U.S. The most often cited reason is that there is a higher risk and liability for operating chassis (as a consequence of the new chassis roadability rules) and the second is the need to cut costs (NCFRP Report 11 and 20). As a result, the traditional chassis supply model is evolving and new models are emerging in the U.S. The transition to new chassis supply models has changed supply, ownership and management of chassis. According to NCFRP Report 20, currently there are five different chassis supply models in the U.S.:

- *Ocean carrier*: chassis are provided and operated by ocean carriers individually as part of their service. This model is the traditional chassis supply model in the U.S. and accounts for 29% of the chassis supply market. Conventionally, ocean container chassis are stored inside the terminals.
- *Co-op pool*: ocean carrier members contribute and share their own chassis to develop a co-op pool. With this model, chassis repair and maintenance activities are performed by a professional management company. This model accounts for 42% of the chassis supply market in the U.S. The advantages of co-op pools include: (1) minimizing chassis mismatches, (2) improving chassis utilization, and (3) reducing terminal storage space requirements. Typically, a co-op's chassis are stored within the terminals.
- *Rental pool*: a third party owns and provides chassis, and users (i.e., ocean carriers and motor carriers) rent chassis at a daily rate. This model accounts for 17% of the U.S. chassis supply market. Rental pool chassis are typically located inside the terminal or very near the terminals.
- *Terminal pool*: marine terminals provide and manage chassis to have more control of the chassis operation to provide a better service for their customers. This model accounts for 6% of the U.S. chassis supply market.
- *Motor carrier*: chassis are owned and managed by the motor carrier or logistics company. This model accounts for 6% of the U.S. chassis supply market. The motor carrier chassis are typically stored at the motor carrier's facility. The motor carrier chassis supply model is the international standard, but it is not as well-established in the U.S.

All models, except the motor carrier chassis supply model, are unique to the U.S. (NCFRP Report 20). The distribution of chassis supply models and their market sizes vary by region (as shown in Figure 4.1). Note that in the Northeast region, the rental pool model is the most prevalent whereas the co-op pool is the most prevalent in all other regions (South Atlantic, Gulf, West Coast and Midwest).

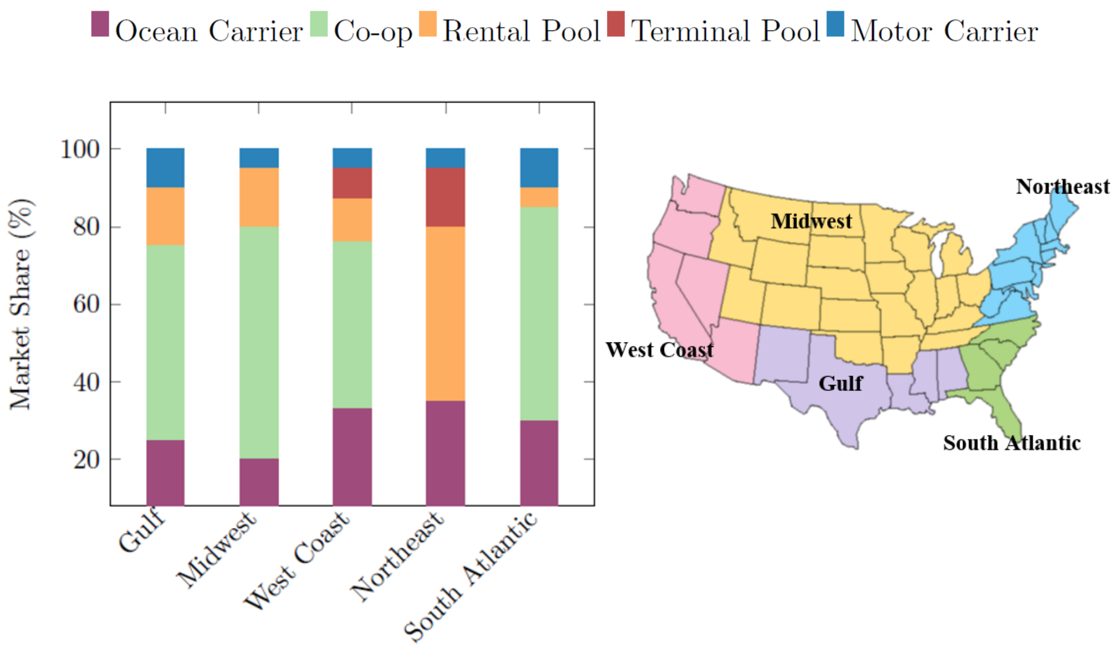


Figure 4.1 Active chassis supply models by region in the U.S. (NCFRP Report 20)

The future chassis supply model in the U.S. will be dependent on the interplay of various supply chain stakeholders (shippers, receivers, ocean carriers, terminal operators, and trucking companies) who have different perspectives and goals. Table 41 shows the advantages and disadvantages of different chassis supply models for key stakeholders. In addition, the public agencies will also play a role in shaping the future chassis supply model because of their interests in land use development, air emissions, and congestion in terminal areas.

Table 4.1 Advantages and disadvantages of chassis supply models for stakeholders (NCFRP Reports 11 and 20, Zumerchik et al. 2010, Rodrigue et al. 2012 and Hartman and Clott, 2015)

Stakeholder	Chassis model	Advantages	Disadvantages
Ocean carrier	*Ocean carrier*	+ Highest operating control by the ocean carrier	- Capital cost of purchasing chassis - Maintenance and repair costs - Storage fees
	Co-op pool, Rental pool, Terminal pool and Motor carrier	+ No capital cost of purchasing chassis + No maintenance and repair costs + No storage fees	-
Trucking company	*Ocean carrier*	+ Chassis are provided as the ocean carrier service and does not have a separate cost	- Greater risk of chassis failure and shortage - Delays in locating and attaching a serviceable chassis at the terminal
	Co-op pool, Rental pool and Terminal pool	+ Better maintenance of chassis and consequently less risk of chassis failure and shortage + Reduce/eliminate delays in locating and attaching a serviceable chassis at the terminal	- Extra chassis-related cost
	Motor carrier	+ Better maintenance of chassis and consequently less risk of chassis failure and shortage + Eliminate delays in locating and attaching a serviceable chassis at the terminal	- Capital cost of purchasing chassis - Maintenance and repair costs - Storage fees
Shipper/ Receiver	*Ocean carrier*	+ No extra charge for chassis-related cost	- Greater risk of delay in the cargo transportation plan due to chassis failure and shortage
	Co-op pool, Rental pool, Terminal pool and Motor carrier	+ Better maintenance of chassis and consequently less risk of delay in the cargo transportation plan due to chassis failure and shortage	- Extra charge for chassis-related cost
Terminal operator	*Ocean carrier*	-	- More terminal storage space requirements - Delays in locating and attaching a serviceable chassis which decrease terminal productivity
	Co-op pool, Rental pool and Motor carrier	+ Reduce/eliminate delays in locating and attaching a serviceable chassis at terminal and improve terminal productivity + Reduce/eliminate terminal storage space requirements and increase twenty-foot equivalent (TEU) per acre inside the terminals	- May need longer queue lanes at the terminal gate since all trucks will have chassis (in models which chassis yards are located outside the terminal or at the motor carrier facility) - Storage space requirements inside the terminal (in models which chassis yards are located inside the terminal)
	Terminal pool	+ Reduce delays in locating and attaching a serviceable chassis at terminal and improve terminal utilization + Reduce terminal storage space requirements and increase twenty-foot equivalent (TEU) per acre inside the terminals	- Capital cost of purchasing chassis - Maintenance and repair costs - Storage space requirements inside the terminal

According to NCFRP Report 20, one of the unanswered questions about the future of the U.S. chassis supply model is: "what will be the future form(s) of chassis supply in the U.S., and what are the implications for chassis supply stakeholders?" This study seeks to answer the second part of this question by developing a new drayage model. The reason why a new model is needed is because previously developed drayage scheduling models did not consider chassis as a separate resource from containers which may need to be picked up from a different location. Although this extension may appear to be simple, it actually makes the mathematical model much more complicated as indicated by Zhang et al. (2011): "the drayage problem becomes extremely complicated if the driver, tractor, chassis, and container are all regarded as separated resources."

This paper develops a drayage model which considers the tractor, chassis, and container as separate resources which are provided in different locations. This new model will allow us to assess the effectiveness of different chassis supply models. In addition, the output from this model will allow us to examine the impact of different chassis supply models on empty movements and air emissions. Other contributions of the model include: (1) ensuring that container and chassis are of the same size and type, and (2) considering the possibility that drayage companies can subcontract the work to independent owner-operators whose trucks will originate from and terminate at different locations. The resulting model is analogous to the multiple traveling salesman problem with time windows (m-TSPTW), but there are three key differences to the traditional m-TSPTW: (1) to complete a container transaction multiple locations may need to be visited, some of which are unknown a priori (e.g. the location of the empty container for the export transaction is not known a priori), (2) the tractor, chassis, and container may reside at the same or different locations, and (3) owner-operator's trucks should return to their original location while drayage company's trucks must return to one of the drayage company's depots. To solve the model in reasonable time, a reactive tabu search (RTS) algorithm combined with an insertion heuristic is developed.

The rest of the paper is organized as follows. A review of the related studies is discussed in Section 2. Section 3 provides the problem description and formulation. Section 4 presents the proposed solution methodology. Section 5 discusses the experimental results. Lastly, conclusions are discussed in Section 6.

4.2 LITERATURE REVIEW

The majority of the drayage-related studies is focused on the static and deterministic version of the problem. That is, these studies consider the drayage problem with a fixed number of jobs and fixed travel times. These studies include the work of Jula et al. (2005) who formulated the drayage problem as m-TSPTW with social constraints and proposed three solution methods: (1) an exact algorithm based on dynamic programming, (2) a hybrid methodology that combines dynamic programming and a genetic algorithm, and (3) an insertion heuristic method. Sterzik and Kopfer (2013) treated containers as transportation resources in their work and proposed a mixed-integer programming model for the drayage problem. The authors developed a tabu search heuristic to solve the problem. Lai et al. (2013) assumed a heterogeneous fleet of vehicles in their work and proposed a mixed-integer linear programing model. They developed new meta-heuristics based on the local search concept. Xue et al. (2014) considered a version of the drayage problem in which tractors and trailers can be separated. With this relaxation, tractors do not have to wait at customers' locations during the packing and unpacking operations. The authors formulated the problem as a classical vehicle routing problem with temporal constraints and developed a solution approach based on tabu search. Xue et al. (2015) extended their previous work by proposing an exact solution method based on combinatorial Benders' cuts algorithm.

The drayage problem is a variation of the pickup-and-delivery problem (PDP) in which vehicle capacity equals one since it involves picking up a container from one place and delivering it to another. Wang and Regan (2002) modeled this version of PDP as an am-TSPTW. They proposed a solution methodology based on a window partition method. Ileri et al. (2006) formulated the drayage problem as a multi-resource PDP. They developed a column generation-based solution method. Imai et al. (2007) modeled the drayage problem as a full-truckload PDP and proposed a new formulation. The authors proposed a Lagrangian relaxation-based heuristic to solve the problem. Caris and Janssen (2009) extended Imai et al.'s model by adding time windows and developed a solution approach based on local search heuristic. Nossack and Pesch (2013) also modeled the drayage problem as a full-truckload PDP with time windows. They developed a 2-stage heuristic solution method; in phase one an initial solution is obtained and this solution is further improved via an ejection chain heuristic in the second stage.

Some studies have focused on the integrated scheduling of loaded and empty container movements in drayage operation. Zhang et al. (2009, 2010) formulated this integrated version as a m-TSPTW. They first proposed a meta-heuristic based on RTS to solve the problem (2009) and then developed a window-partition based solution method (2010) inspired by Wang and Regan (2002). Zhang et al. (2011) further extended the problem by assuming that the available number of empty containers at the depot is limited and developed a solution method based on RTS. Braekers et al. (2013) proposed a sequential and an integrated approach to solve the drayage problem. They developed a single-phase and a two-phase deterministic annealing algorithm to solve their proposed model. Their results showed that the integrated approach yield results that are superior to those obtained using the sequential approach. Braekers et al. (2014) extended their previous work by considering the drayage problem with two objectives: (1) minimizing the number of vehicles, and (2) minimizing the total distance. Three solution methods were developed to solve the problem: (1) an iterative method, (2) a deterministic annealing algorithm, and (3) a hybrid deterministic annealing and tabu search algorithm.

A few studies have addressed the dynamic and stochastic version of the drayage problem. That is, these studies consider the drayage problem with unknown demands, uncertain travel times or uncertain activity durations. Máhr et al. (2010) compared an agent-based method and an online optimization method for a drayage problem with uncertainty in service-times and job-arrivals. They concluded the agent-based method outperforms the online optimization method in cases with moderate service time and job-arrival uncertainties. Zhang et al. (2011) assumed customer requests are not known a priori in their work. At the beginning of the planning horizon the problem is solved using the current knowledge about customer requests. Then, this solution is updated by solving the problem at several decision epochs. Escudero et al. (2011, 2013) proposed a dynamic approach to solve drayage problem by using the real-time knowledge about the position of the vehicles. Their solution approaches involved taking snapshots of prevailing situations, using the captured information to update the state of all tasks and vehicles, and then rerunning the optimization model. Marković et al. (2014) proposed a model that takes into consideration uncertain truck roundtrip durations and unknown train departure times. Their model's objective function minimizes the expected cost which consists of: (1) expected storage cost, (2) expected in-terminal operation cost, and (3) expected penalty cost for late delivery. The authors proposed two solution methods: (1) local search based on the interior point, and (2) a hybrid genetic algorithm. Zhang et al. (2014) studied the dynamic drayage problem with flexible orders. They modified the graph introduced by Zhang et al. (2009) and introduced a temporary vertices set to describe the truck statuses. Based on this graph, the dynamic drayage problem was formulated as an am-TSPTW. The authors provided two strategies to solve the problem when interruptions occur: (1) append, and (2) re-optimization. The append strategy assigns newly arrived orders to trucks, and the re-optimization strategy re-solves the drayage problem with updated information which could be done via commercial software, simple discretization scheme, or window partitioning scheme. Their results indicated that the re-optimization strategy, particularly the one based on the window partitioning scheme, outperformed the append strategy.

To reduce gate congestion, several terminals have implemented the truck appointment system to even out demand. To address this practice, a few studies considered time window constraints at marine container terminals (via the truck appointment system), such as the work by Namboothiri and Erera (2008) and Shiri and Huynh (2016). Namboothiri and Erera (2008) considered a PDP with a truck appointment system. Their proposed solution approach involved the use of the column generation method. Shiri and Huynh (2016) studied the integrated scheduling of loaded and empty container movements in drayage operation with a truck appointment system. They formulated the drayage problem as an extension of the m-TSPTW and proposed a RTS meta-heuristics to solve the problem.

A few studies have examined the collaboration effect between drayage companies. Sterzik et al. (2015) studied the effect of sharing empty containers between drayage companies. They solved the problem using a tabu search heuristic. Their results indicated that sharing empty containers will yield lower total costs. Wang and Kopfer (2015) investigated the dynamic version of the drayage problem in which companies can exchange customer requests. The authors developed two rolling horizon planning solution methods. Their results showed that collaborative transportation planning yielded better results than isolated planning.

In recent years, a number of studies have addressed the drayage problem considering different container size. Vidović et al. (2011, 2012), Popović et al. (2014) and Zhang et al. (2015) assumed that a truck is equipped with a slider chassis which can carry either one 40-ft container or two 20-ft containers. Vidović et al. (2011) formulated the multi-container-size drayage problem as a multiple matching problem. They developed a heuristic approach based on matching utilities to solve the problem. Vidović et al. (2012) provided two mathematical formulations to formulate the multi-container-size drayage problem: (1) multiple assignment formulation, and (2) general mixed integer programming formulation. Popović et al. (2014) extended the work of Vidović et al. (2011, 2012) by proposing a variable neighborhood search heuristic to solve the multi-container-size drayage problem with time windows. Zhang et al. (2015) modeled the multi-container-size drayage problem as a sequence-dependent multiple-traveling salesman problem with social constraints. They developed three tree search procedures and an improved reactive tabu search algorithm to solve the problem. Vidović et al. (2016) extended the work of Vidović et al. (2011) by introducing time windows and assuming that a truck is capable of transporting any arbitrary number of 20-ft and 40-ft containers. To solve the problem, the authors developed a variable neighborhood search heuristic. Funke and Kopfer (2016) also addressed the multi-container-size version of the drayage problem and proposed a mixed-integer linear programing model. They solved their proposed model using CPLEX for small-sized problems.

The focus of this study is most closely related to the work performed by Chung et al. (2007), Vidović et al. (2011, 2012, and 2016), Popović et al. (2014) and Zhang et al. (2015) in that it focuses on solving the multi-container-size drayage problem. However, this study is different and contributes to the literature in several aspects: (1) in aforementioned studies the tractor and container are considered as a joint resource, but in this work tractors, containers and chassis are treated as separate resources which requires a model that solves the scheduling of tractors, loaded containers, empty containers and chassis jointly, (2) none of the aforementioned studies considered chassis yard as a separate location that must be visited in order to have the proper chassis (in terms of size and type) for the container to be picked up or delivered, and (3) a heterogeneous mix of drayage vehicles (from company fleet and owner-operators) with different start and end locations is considered; drayage company's trucks start at company's depot and should return to one of the company's depots whereas owner-operators' trucks should return to the same location from where they originated. To our knowledge, our proposed model is the first to solve the scheduling of tractor, loaded container, empty container and chassis movements in drayage operation in an integrated manner. Such a model will allow for the assessment of the different U.S. chassis supply models.

4.3 PROBLEM DESCRIPTION AND FORMULATION

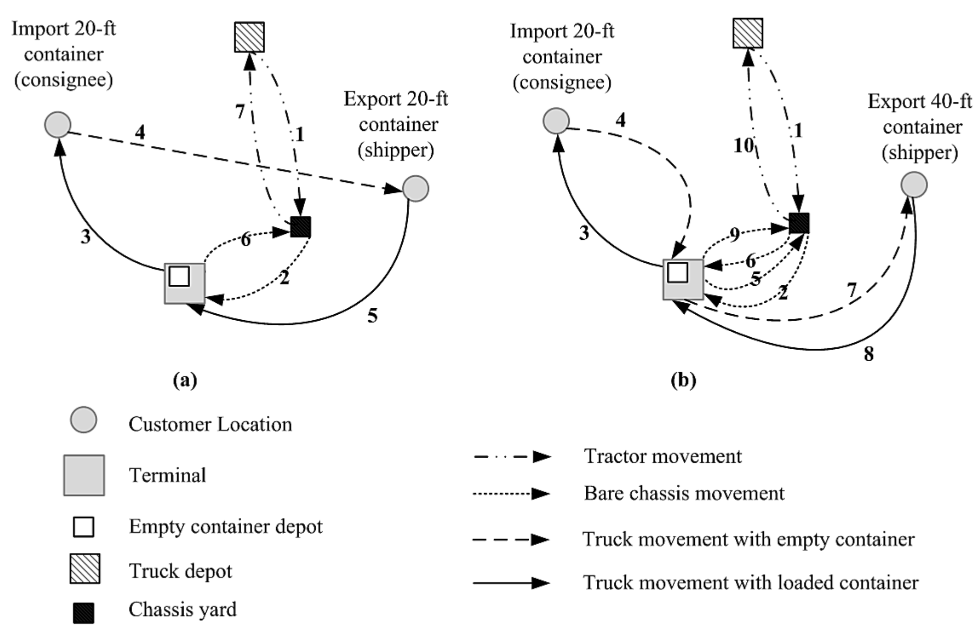
4.3.1 Independent Owner-operators

In practice, U.S. ports are served by both drayage companies' and owner-operators' trucks. A survey at the Ports of New York/New Jersey indicated that 73% of the drayage truck drivers are owner-operators (Bensman and Bromberg, 2009). Another survey at the Jacksonville Port indicated that 67% of the drivers are owner-operators (Jaffee and Rowley, 2009). The demand for owner-operators increased in U.S. port cities after implementation of the U.S. Shipping Act of 1984 which permitted door-to-door service contracts (Peoples and Talley, 2004). The current business model entails customers (shippers or consignees) procuring the service of a drayage company to pick up an import container or deliver an export container. The drayage company can either utilize its own driver or sub-contract the work to an owner-operator who provides his own vehicle. The two major benefits for drayage companies in using owner-operators are (APGST Summary Report, 2013): (1) lower up-front capital investment and the financial risk, and (2) greater flexibility in meeting the seasonal and unexpected demands. In this study, the heterogeneous mix of drayage vehicles that comes from company fleets and independent owner-operators is explicitly considered; specifically, the consideration that these two types of vehicles have different characteristics with respect to their starting and terminating locations and cost of operation. That is, drayage company's trucks must start at company's depot and should return to one of the company's depots whereas owner-operators' trucks must start from owner-operators' facilities and should return to the same facility where they originated. Also, different costs are considered for the two types of trucks to ensure that a drayage company utilizes all of its trucks first before subcontracting the work to owner-operators.

4.3.2 Drayage Problem and Assumption

Figure 4.2a shows a typical journey for a drayage truck with the assignment to pick up an import container and deliver an export container. In this example, there is one container terminal, one empty container depot inside the terminal, one off-terminal chassis yard, one truck depot, and two customers (a consignee with a 20-ft import container pickup request and a shipper with a 20-ft export container delivery request). The sequence of the drayage movements are indicated by the respective numbers on the links. The sequence begins with the truck going to the chassis yard (link 1) to pick up a 20-ft chassis and then traveling to the terminal (link 2) to pick up the 20-ft import loaded container. The truck then transports the loaded container to the consignee (link 3) where the container will be unpacked. At this point, the empty container can either be returned to the empty container depot or used for another job. In this example, since the next job requires an empty container of 20-ft the truck can transport the empty container from the consignee to the shipper (link 4). This strategy is known as "street-turns" and implementing such a strategy will result in fewer gate transactions at the terminal, better driver productivity, and more efficient equipment utilization. After the container is packed, the truck then transports the loaded container to the container terminal (link 5). Lastly, the truck goes to the chassis yard (link 6) to drop off the chassis and then return to its truck depot (link 7). It should be noted that empty containers are typically not shared between ocean carriers; thus, in this example, the truck will not be able to use the same empty container unless import and export moves involve the same ocean carrier.

Figure 4.2b illustrates a case where the size of the empty container needed for the export move is different from the size of the empty container at the consignee's location. In this situation, after fulfilling consignee's order, the truck needs to travel to the empty container depot (link 4) which is located inside the terminal in this example to drop off the empty container. Next, the truck needs to travel to the chassis yard (link 5) to swap chassis, from 20-ft to 40-ft. Then the truck needs to travel to the empty container depot (link 6) to pick up a 40-ft empty container. Lastly, the truck travels to the shipper's location (link 7) to fulfill the shipper's order. The moves indicated by links 8, 9, and 10 in Figure 4.2b are identical to those indicated by links 5, 6, and 7 in Figure 4.2a.



4.2 Illustration of drayage truck movements: (a) import 20-ft container and export 20-ft container; (b) import 20-ft container and export 40-ft container

In the illustrated example, chassis are stored at an off-terminal yard and empty containers are stored in an empty container depot located inside the terminal. If the chassis yard is located inside the terminal or at the motor carrier's facility and the empty container depot is located outside of the terminal, then the mentioned drayage movements in Figures 4.2a and 4.2b are still applicable. The only difference is the location where the empty container and chassis moves are performed.

The aim of this study is to determine the optimal drayage sequence for each truck, considering street-turns, to fulfill all the transportation orders from customers. The scheduling decision to be made by the drayage company on a daily basis is the focus of this study. The objective is to minimize the total drayage operation time. A customer is allowed to request one or more of the following jobs: import pickup or export delivery. In this study, we assume that trucks are required to stay at the customer's locations during the packing and unpacking operation. The drayage company is considered to have a limited number of trucks and multiple truck depots. As mentioned, it is assumed that the drayage company can subcontract any work it deems necessary. The drayage company's trucks must start at one of the company's depots and should return to one of the company's depots. It is assumed that trucks will choose the depot nearest to their last location as the final depot. The owner-operators' trucks should return to the same location from where they initially originated. It is assumed that moves involve different container sizes. Customers are allowed to request specialty chassis. Based on the five chassis supply models explained earlier, three different chassis yard locations are considered: (1) inside the terminal, (2) outside the terminal, and (3) at the motor carrier's facility. In addition, two different scenarios for the storage of empty containers are considered: (1) inside the terminal, and

(2) outside the terminal. It is assumed that the empty containers are shared among ocean carriers; this assumption has been made in many other drayage studies to make the model tractable, such as Zhang et al. (2010, 2011) and Xue et al. (2014, 2015). Finally, it is assumed that all jobs are known a priori and all travel times are fixed, and thus, the drayage problem being studied in this paper is static and deterministic.

4.3.3 Notation and Abbreviations

The notations used to describe the drayage problem are provided in Table 4.2.

Table 4.2 Drayage model notations

Notation	Notation description
N_D	Set of truck depot nodes
$N_{D'}$	Set of owner-operator facility nodes
N_I	Set of import job nodes
N_E	Set of export job nodes
N_J	Set of job nodes, $N_J = N_I \cup N_E$
T^i	Set of trucks initially located at truck depot/owner-operator facility node i
T	Set of all trucks, $\boldsymbol{T} = \bigcup_{i \in N_D \cup N_{D'}} T^i$
T^{DC}	Set of drayage company's trucks, $T^{DC} = \bigcup_{i \in N_D} T^i$
n_i	Number of trucks initially located at truck depot/owner-operator facility node i
$[L_i,U_i]$	Time window of job node i at the customer location
ST_i	Service time of node i
TT_{ij}	Transfer time on arc (i, j)
W^k	A constant, 1 for drayage company's trucks and 5 for owner-operators' trucks
M	A sufficiently big constant

To simplify references to the chassis models, the following abbreviations will be used hereafter (Table 4.3).

Table 4.3 Abbreviations of chassis supply models

Abbreviation	Abbreviation description
OC	Ocean carrier
COOP	Co-op pool
RONT	Rental pool with chassis yard located on (inside) the terminal (see illustration in Figures 4.6a and 4.6d)
ROFFT	Rental pool with chassis yard located off (outside) the terminal (see illustration in Figures 4.6b and 4.6e)
T	Terminal pool
MC	Motor carrier

4.3.4 Graphical Representation of the Drayage Problem

The formulation of the drayage problem is based on a graph representation of the various drayage activities. This graphical representation is adapted from the work of Zhang et al. (2010). Drayage activities can be classified as follows.

1. Activities that should be performed for each type of job at the customer location. These activities include: (1) unmounting loaded/empty container from the truck, (2) unpacking/packing the container, and (3) mounting loaded/empty container.
2. Activities that should be performed for each type of job between the customer location and terminal and at the terminal. These activities include: (1) transporting the loaded container to the customer/terminal, (2) waiting in queue at the terminal gate, and (3) picking up/dropping off loaded container at the terminal.
3. Activities that should be performed after the completion of job *i* activities and before the commencement of job *j* activities. These activities include picking up a chassis from the chassis yard or picking up an empty container from the empty container depot.

Type 1 activities occur at the nodes, and types 2 and 3 activities occur on the arcs. To construct an optimal schedule route for each truck, let $G(N, A)$ be a graph that depicts the various drayage activities, where N is the set of nodes and A is the set of arcs. The set of nodes consists of depots (where drayage company's trucks originate and terminate), owner-operator facilities (where owner-operator's trucks originate and terminate), and jobs. The depot nodes and owner-operator facility nodes specify the number of trucks initially located at the truck depots and at the owner-operators' facilities, respectively. The job nodes represent activities that should be performed for each type of job, import pickup (N_I) or export delivery (N_E), at the customer locations (type 1 activities). The time it takes to complete all of these activities is called the service time (ST_i). The activity and time associated with import and export job nodes are provided in Table 4.4.

Table 4.4 Activity and time associated with import and export job nodes

Job Node *i*	**Activity and time at customer location**
$i \in N_I$	1. Unmount loaded container from truck (time to unmount container) 2. Customer unpack container (time to unpack container) 3. Mount empty container to truck (time to mount container)
$i \in N_E$	1. Unmount empty container from truck (time to unmount container) 2. Customer pack container (time to pack container) 3. Mount loaded container to truck (time to mount container)

Another attribute of the job nodes is the time window, denoted by $[L_i, U_i]$. The time window of a job node indicates the time interval that activities at this node (at customer location) should start within. For both types of job nodes, activity 1 in Table 4.4 should start within the corresponding time window.

Table 4.5 Transfer time of arc (i, j) in chassis supply model where the chassis yard and the empty container depot are located inside the terminal

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	- Travel time between TD[1] *i* and TR[2] - Gate queuing time - Time to pick up chassis and loaded container *j* (TR turn time) - Travel time between TR and CL[3] *j*	- Travel time between TD *i* and TR - Gate queuing time - Time to pick up chassis and an empty container (TR turn time) - Travel time between TR and CL *j*
	N_I	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off chassis and empty container *i* (TR turn time) - Travel time between TR and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i*, drop off chassis *i* and pick up chassis *j* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i*, drop off chassis *i*, pick up chassis *j* and pick up an empty container (TR turn time) - Travel time between TR and CL *j*
	N_E	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and chassis (TR turn time) - Travel time between TR and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* - ELSE - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i*, drop off chassis *i*, pick up chassis *j* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up an empty container (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i*, drop off chassis *i*, pick up chassis *j* and pick up an empty container (TR turn time) - Travel time between TR and CL *j*

[1]TD: Truck Depot [2]TR: Terminal [3]CL: Customer Location

The arc (i, j) represents the transfer time between two nodes. Transfer time on arc (i, j) includes: (1) the time it takes to complete type 2 activities, and (2) the time it takes to complete type 3 activities between nodes i and j. The transfer time on arc (i, j) depends on the combination of nodes that occur at i and j, as well as the location of chassis yard and empty container depot. The transfer time for all possible combinations is provided in Tables 4.5, 4.6, 4.7 and 4.8. Tables 4.5 and 4.6 describe situations where the empty container depot is located inside the terminal, and the chassis yard is located inside the terminal and outside the terminal/at the motor carrier facility, respectively.

Table 4.6 Transfer time of arc (*i*, *j*) in chassis supply models where chassis yard is located outside the terminal or at motor carrier's facility, and the empty container depot is located inside the terminal

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	- Travel time between TD[1] *i* and CHS[2] - Time to pick up chassis - Travel time between CHS and TR[3] - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL[4] *j*	- Travel time between TD *i* and CHS - Time to pick up chassis - Travel time between CHS and TR - Gate queuing time - Time to pick up an empty container - Travel time between TR and CL *j*
	N_I	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off the empty container - Travel time between TR and CHS - Time to drop off the chassis - Travel time between CHS and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i* - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off empty container *i* - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis j - Travel time between CHS and TR - Gate queuing time - Time to pick up an empty container (TR turn time) - Travel time between TR and CL *j*
	N_E	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* - Travel between TR and CHS - Time to drop off chassis - Travel time between CHS and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off container *i* - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up an empty container (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* (TR turn time) - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and TR - Gate queuing time - Time to pick up an empty container - Travel time between TR and CL *j*

[1]TD: Truck Depot [2] CHS: Chassis Yard [3]TR: Terminal [4]CL: Customer Location

Table 4.7 Transfer time of arc (i, j) in chassis supply model where chassis yard is located inside the terminal, and the empty container depot is located outside the terminal

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	- Travel time between TD[1] *i* and TR[2] - Gate queuing time - Time to pick up chassis and loaded container *j* (TR turn time) - Travel time between TR and CL[3] *j*	- Travel time between TD *i* and TR - Gate queuing time - Time to pick up chassis (TR turn time) - Travel time between TR and ECD[4] - Time to pick up an empty container - Travel time between ECD and CL *j*
	N_I	- Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and TR - Gate queuing time - Time to drop off chassis (TR turn time) - Travel time between TR and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and TR - Gate queuing time - Time to drop off chassis *i*, pick up chassis *j* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and CL *j* *ELSE* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and TR - Gate queuing time - Time to drop off chassis *i* and pick up chassis *j* (TR turn time) - Travel time between TR and ECD - Time to pick up an empty container - Travel time between ECD and CL *j*
	N_E	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and chassis (TR turn time) - Travel time between TR and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* - *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i*, drop off chassis *i*, pick up chassis *j* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* (TR turn time) - Travel time between TR and ECD - Time to pick up an empty container - Travel time between ECD and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i*, drop off chassis *i* and pick up chassis *j* - Travel time between TR and ECD - Time to pick up an empty container - Travel time between ECD and CL *j*

[1]TD: Truck Depot [2]TR: Terminal [3]CL: Customer Location [4]ECD: Empty container depot

Table 4.8 Transfer time of arc (i, j) in chassis supply models where chassis yard is located outside the terminal or at motor carrier's facility, and the empty container depot is located outside the terminal

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	- Travel time between TD[1] *i* and CHS[2] - Time to pick up chassis - Travel time between CHS and TR[3] - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL[4] *j*	- Travel time between TD *i* and CHS - Time to pick up chassis - Travel time between CHS and ECD[5] - Time to pick up an empty container - Travel time between ECD and CL *j*
	N_I	- Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and CHS - Time to drop off the chassis - Travel time between CHS and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and CL *j* *ELSE* - Travel time between CL *i* and ECD - Time to drop off empty container *i* - Travel time between ECD and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and ECD - Time to pick up an empty container - Travel time between ECD and CL *j*
	N_E	- Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* - Travel between TR and CHS - Time to drop off chassis - Travel time between CHS and TD *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* and pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and TR - Gate queuing time - Time to pick up loaded container *j* (TR turn time) - Travel time between TR and CL *j*	*IF* chassis *i* can be used for container *j* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* (TR turn time) - Travel time between TR and ECD - Time to pick up an empty container - Travel time between ECD and CL *j* *ELSE* - Travel time between CL *i* and TR - Gate queuing time - Time to drop off loaded container *i* (TR turn time) - Travel time between TR and CHS - Time to drop off chassis *i* and pick up chassis *j* - Travel time between CHS and ECD - Time to pick up an empty container - Travel time between ECD and CL *j*

[1]TD: Truck Depot [2]CHS: Chassis Yard [3]TR: Terminal [4]CL: Customer Location [5]ECD: Empty container depot

Tables 4.7 and 4.8 describe the situations where the empty container depot is located outside the terminal, and the chassis yard is located inside the terminal and outside the terminal/at the motor carrier facility, respectively. It should be noted that chassis can be used for job j after job i if the container in jobs i and j have the same size and type for all chassis supply models, except for the OC model. With the OC model, the ocean carrier does not share chassis, and thus, to use the same chassis for jobs i and j both jobs must involve the same ocean carrier in addition to having the same container size and chassis type.

4.3.5 Mathematical Formulation

The mathematical formulation of the drayage problem is based on the graphical representation presented in the previous section. Its decision variables, objective function, and constraints are presented below.

$$x_{ij}^{k} = \begin{cases} 1 & \text{If job node } i \text{ and job node } j \text{ are served consecutively by truck } k \\ 0 & \text{Otherwise} \end{cases}$$

s_i = Time that the first activity on node i is started

$$\begin{aligned} \text{Minimize } & \sum_{k \in T^{DC}} \sum_{i \in N_D} \sum_{j \in N_J} s_j \times W^k \times x_{ji}^k + \sum_{k \in T^i} \sum_{i \in N_{D'}} \sum_{j \in N_J} s_j \times W^k \times x_{ji}^k - \\ & \sum_{k \in T^i} \sum_{i \in N_D \cup N_{D'}} \sum_{j \in N_J} s_j \times W^k \times x_{ij}^k + \sum_{k \in T^i} \sum_{i \in N_D \cup N_{D'}} \sum_{j \in N_J} TT_{ij} \times W^k \times x_{ij}^k + \\ & \sum_{k \in T^{DC}} \sum_{i \in N_D} \sum_{j \in N_J} (ST_j + TT_{ji}) \times W^k \times x_{ji}^k + \sum_{k \in T^i} \sum_{i \in N_{D'}} \sum_{j \in N_J} (ST_j + TT_{ji}) \times W^k \times x_{ji}^k \end{aligned} \tag{4.1}$$

$$\sum_{j \in N_J} \sum_{k \in T^i} x_{ij}^k \le n_i \qquad \forall i \in N_D \cup N_{D'} \tag{4.2}$$

$$\sum_{j \in N_J} x_{ij}^k \le 1 \qquad \forall i \in N_D \cup N_{D'}, \forall k \in T^i \tag{4.3}$$

$$\sum_{j \in N_J} x_{ij}^k = \sum_{d \in N_D} \sum_{j \in N_J} x_{jd}^k \qquad \forall i \in N_D, \forall k \in T^i \tag{4.4}$$

$$\sum_{j \in N_J} x_{ij}^k = \sum_{j \in N_J} x_{ji}^k \qquad \forall i \in N_{D'}, \forall k \in T^i \tag{4.5}$$

$$\sum_{k \in T} \sum_{j \in N_J} x_{ji}^k + \sum_{k \in T^j} \sum_{j \in N_D \cup N_{D'}} x_{ji}^k = 1 \qquad \forall i \in N_J \tag{4.6}$$

$$\sum_{k \in T} \sum_{j \in N_J} x_{ij}^k + \sum_{k \in T^{DC}} \sum_{j \in N_D} x_{ij}^k + \sum_{k \in T^j} \sum_{j \in N_{D'}} x_{ij}^k = 1 \qquad \forall i \in N_J \tag{4.7}$$

$$x_{di}^k + \sum_{j \in N_J} x_{ji}^k = \sum_{j \in N_J} x_{ij}^k + \sum_{j \in N_D} x_{ij}^k \qquad \forall i \in N_J, \forall d \in N_D, \forall k \in T^d \tag{4.8}$$

$$x_{di}^k + \sum_{j \in N_J} x_{ji}^k = \sum_{j \in N_J} x_{ij}^k + x_{id}^k \qquad \forall i \in N_J, \forall d \in N_{D'}, \forall k \in T^d \tag{4.9}$$

$$TT_{ij} - (1 - x_{ij}^k) \times M \le s_j \qquad \forall i \in N_D \cup N_{D'}, \forall j \in N_J, \forall k \in T^i \tag{4.10}$$

$$s_i + TT_{ij} + ST_i - (1 - x_{ij}^k) \times M \le s_j \qquad \forall i, j \in N_J, \forall k \in T \tag{4.11}$$

$$L_i \le s_i \le U_i \qquad \forall i \in N_J \tag{4.12}$$

$$x_{ij}^k \in \{0,1\} \qquad \forall i, j \in N_J \cup N_D \cup N_{D'}, \forall k \in T \tag{4.13}$$

$$s_i \ge 0 \qquad \forall i \in N_J \tag{4.14}$$

Equation (4.1) is the objective function which seeks to minimize the weighted sum of the drayage operation time. W^K is set to 1 for drayage company's trucks and 5 for owner-operators's trucks. These weights are chosen to ensure that all drayage company's trucks are used first before owner operators' trucks are used. This approach forces the model to give priority to drayage company's trucks. In the event that the drayage company does not have sufficient number of trucks to meet the customers' demands, then owner-operators' trucks are used. The first and second terms of the objective function are the start times of the trucks' last jobs in their routes. The third term is the start times of the trucks' first jobs after leaving their initial location. The difference between start times of a truck's last and first jobs represents the operation time of this truck between its first and last jobs. The fourth term is the transfer time between the initial depot/facility of trucks and the location of trucks' first jobs. The fifth term applies to drayage company's trucks; it is the service time of the trucks' last jobs and transfer time between the location of these jobs and the nearest truck depot. The sixth term applies to owner-operators' trucks; it is the service time of the trucks' last jobs and transfer time between the location of these jobs and their facilities. In this paper, it is assumed that transfer time and service time are valued equally (e.g., Zhang et al., 2010; Nossack and Pesch, 2013; Sterzik et al., 2015). Constraint (4.2) is the capacity constraint for truck depots/facilities which ensures that the number of routes started from each truck depot/facility is less than or equal to the initial number of trucks at that depot/facility. Constraint (4.3) ensures that each truck is used at most once. Constraint (4.4) guarantees that each truck that starts its route from one of the drayage company's depots will end at one of drayage company's depots. Constraint (4.5) guarantees that all owner-operators' trucks return to the same facility where they originated. Constraints (4.6) and (4.7) ensure that each customer is visited exactly once. Constraints (4.8) and (4.9) state that if a truck enters a job node (i.e. customer location), then it must leave it to maintain node conservation. Constraints (4.10) and (4.11) enforce the time relationship among consecutive nodes along a route. Constraint (4.12) restricts the start time of job nodes to their time windows. Lastly, Constraints (4.13) and (4.14) define the domain of the decision variables.

4.3.6 Modeling Emissions

Emissions of vehicles are proportional to the amount of fuel consumed, which itself is a function of several factors such as vehicle travel distance, vehicle weight, vehicle speed, vehicle type and road characteristics (e.g. grade). For example, an increase in a vehicle's payload will require greater fuel consumption to travel at the same speed. There exists a variety of models that estimate vehicle emissions. They differ from one another in the number and type of parameters considered and/or in how fuel consumption or emissions are estimated. A survey of vehicle emission estimation models can be found in the work by Demir et al. (2011). One of the comprehensive emission estimation models was developed by Hickman et al. (1999) called Methodology for Calculating Transport Emissions and Energy Consumption (MEET) to assess various emissions for different types of transport modes. This study uses the MEET model due to its ability to account for different vehicle types and vehicle weights. The MEET model is used to calculate the amount of carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOC, also referred to as hydrocarbons), oxides of nitrogen (NO_X) and particulate matter (PM).

The MEET model first estimates emission factors for the base conditions which assumes that the vehicle is unloaded and is traveling on a level road as given in Equation (4.15). The primary input is speed. The values for the constant and all other coefficients depend on the vehicle type, vehicle weight, and air pollutant; these values can be found in the work by Hickman et al. (1999).

$$\varepsilon = K + av + bv^2 + cv^3 + \frac{d}{v} + \frac{e}{v^2} + \frac{f}{v^3} \tag{4.15}$$

where

ε = the rate of emissions in g/km for an unloaded freight vehicle traveling on a level road,

v = the average speed of the vehicle in km/h,

K = constant,

$a - f$ = coefficients.

To account for situations when the vehicle is loaded, the load factor can be calculated as follows.

$$\phi(\gamma, v) = K + n\gamma + p\gamma^2 + q\gamma^3 + rv + sv^2 + tv^3 + \frac{u}{v} \tag{4.16}$$

where

$\phi(\gamma, v)$ = the load correction factor,

γ = the gradient in percent,

$n - u$ = coefficients.

The rate of emissions for loaded vehicles in *g*/*km* is thus a product of Eqs. 15 and 16.

$$\varepsilon_l = \phi(\gamma, v) \times \varepsilon \tag{4.17}$$

The vehicle emissions for the entire journey in *g* is calculated as follows.

$$E = \varepsilon_l \times L \tag{4.18}$$

where

E = total emissions in *g*,

L = total distance travelled by vehicle in *km*.

This study used the MEET model parameter values and coefficients as applied by Kim and Van Wee (2014) because their MEET model application also dealt with drayage and intermodal operations. Readers are referred to their work for additional details.

4.4 SOLUTION METHODOLOGY

The proposed mathematical model is NP-hard since it is an extension of the m-TSPTW which has been shown to be NP-hard. While a number of meta-heuristics could be used to solve the proposed drayage model, RTS is used in this study because it has been found to be successful in solving drayage problems (Zhang et al., 2009, 2011, 2015, Shiri and Huynh, 2016), as well as vehicle routing problems (Chiang and Russell, 1997; Cordeau et al., 2001; Osman and Wassan, 2002; Wassan et al., 2008). The framework of the proposed solution methodology is shown in Figure 4.3. It consists of two phases. Phase 1 involves constructing an initial solution which is based on Solomon's work (1987). The solution obtained from phase 1 is further improved in phase 2 via RTS that is based on Battiti and Tecchiolli's work (1994).

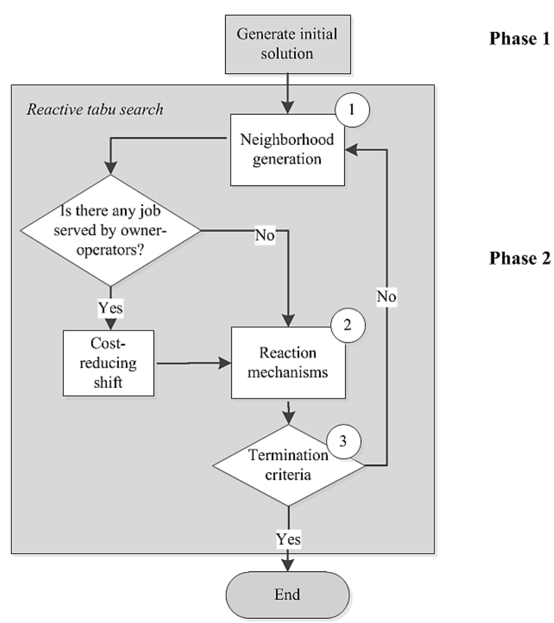


Figure 4.3 Flowchart of developed solution methodology

Tabu search (TS) is a local-search meta-heuristic originally proposed by Glover (1986). TS uses neighborhood search and prohibition-based techniques to explore the solution space for finding the optimal solution. TS starts from an initial solution and explores the solution space by moving from the current solution to the best solution in its neighborhood. The new solution becomes the current solution in the next iteration. Since the new solution does not necessarily have a better objective function than the current solution, cycling may occur. TS prevents cycling and getting trapped in local optima by recording some attributes of recently visited solutions in a tabu list and forbidding local search moves that would result in a solution with these attributes. The forbidden moves are kept in the tabu list for a period of time, known as tabu tenure (*tt*). However, tabu restriction is not entirely forbidden; it can be overridden when a tabu move results in a solution better than all visited solutions.

Reactive search was introduced by Battiti et al. (1994) to improve TS by using the history of already visited solutions to guide the search. This type of TS is called reactive tabu search (RTS). Tabu tenure is changed dynamically in RTS by tracking the number of repeated solutions. Moreover, an escape mechanism is triggered when the search is trapped in the solution space characterized as a "chaotic attractor basin." The following sections provide specific details regarding this study's implementation of RTS components.

The RTS solution algorithm described in this study is different from our previous RTS solution algorithm (Shiri and Huynh, 2016) in that 1) it does not have a truck appointment booking procedure, and 2) it introduces a new shifting process called *cost-reducing*.

4.4.1 Initial Solution Generation Procedure

Phase 1 (shown in Figure 4.3) involves generating an initial solution via an insertion heuristic. Solomon (1987) proposed several tour-building heuristics for vehicle routing problems with time windows. Among those, the one that yielded the best result was the insertion heuristic. This study adapts this heuristic for the drayage problem. The basic idea is that a route is constructed from a depot or facility and job nodes are inserted one at a time into this route until no more insertion is feasible with respect to Constraint (4.12). This process is repeated until all job nodes are assigned to routes. In this study, in constructing a new route, the transfer time between each depot node (with trucks that have not been assigned a route) and each unassigned job node is considered. Specifically, the pair of depot node and job node which has the lowest transfer time is selected. In the scenario that the drayage firm subcontracts the work to an owner-operator, then the transfer time between that owner-operator's facility node and each unassigned job is considered and the pair with the lowest transfer time is selected. Solomon's (1987) heuristic was modified for the proposed drayage problem because trucks do not start and end at the same location. Specifically, if a route is served with a drayage company's truck, then the nearest depot to the location of the last job node is added to the end of this route. If a route is served with an owner-operator's truck, then the facility that the truck originates from is added to the end of the route.

Let $UA = \{u_1, u_2, \ldots, u_n\}$ be the set of unassigned job nodes and let R_C be the current route. To construct a route from depot i_0, $R_C = \{i_0\}$, u_i is inserted after the depot node if it is feasible with respect to Constraint (4.12). Then the route is updated, $R_C = \{i_0, u_i, i_2\}$; note that the last node, i_2, is updated and selected based on location of the last job and whether the truck belongs to the drayage company or owner operator. The cost (in terms of drayage operation time) of the insertion is obtained using the following equation.

$$C_i = \min\{c(i_0, u_i, i_2)\} \qquad (4.19)$$

where $c(i_0, u_i, i_2)$ is calculated using Equation (4.1).

Suppose $R_C = \{i_0, i_1, i_2, \ldots, i_m, i_{m+1}\}$ is the current route after m job nodes have been inserted (i_{m+1} is the depot or facility node). For the unassigned u_i, the feasibility of inserting this job in different positions in R_C is checked against constraint (4.12), and then the cost of the insertion is obtained using the following equation:

$$C_i = \min\{c(i_{p-1}, u_i, i_p)\} \qquad p = 1, \ldots, m+1 \qquad (4.20)$$

where $c(i_{p-1}, u, i_p)$ is calculated using Equation (4.1).

During the insertion procedure, among the unassigned job nodes, the lowest-cost one is selected as follows.

$$k = \arg\min_{i \in 1..n} \{C_i\} \qquad (4.21)$$

4.4.2 Moves and Neighborhood Generation Mechanism

Each solution in our problem corresponds to a set of routes that serves a set of customers while all constraints are satisfied. As mentioned, RTS explores the feasible region to improve the solution. It is done via neighborhood generation mechanisms that generate a set of neighboring solutions in the feasible region. Each problem needs a specific neighborhood generation mechanism to generate the neighborhood of the current solution. For our problem, moving job nodes between routes or changing their positions within a route can provide a neighboring solution (Figure 4.4). The neighborhood generation mechanism used in this paper is the λ-interchange mechanism introduced by Osman (1993) which exchanges a subset of job nodes between routes to generate a neighboring solution. Let $S = \{R_1, R_2,\ldots, R_v\}$ be a solution. First, two routes are selected from the solution S randomly, say R_p and R_q. Then two subsets of nodes (S_p and S_q) are chosen from the nodes in R_p and R_q ($S_p \subseteq R_p$ and $S_q \subseteq R_q$) to be exchanged between these two routes. This leads to generate two new routes, R'_p and R'_q, and a new solution S'. We implemented λ-interchange mechanism with $\lambda = 1$. The *1-interchange* mechanism exchanges a subset of S_p of size $|S_p| \leq 1$ from R_p with a subset of S_q of size $|S_q| \leq 1$ from R_q. This mechanism invokes two processes to generate neighboring solutions, shift and interchange processes (shown in Figures 4.4a and 4.4b). The shift process is represented by (1,0) or (0,1) operators. These operators move one job node from a route to another route. The interchange process is represented by the (1,1) operator which exchanges one job node between two routes. In both processes the best insertion place in the new route is selected to insert the job node. To improve the quality of the solution, this study also implemented a mechanism called Local-shift (Figure 4.4c) introduced by Wassan et al. (2008). The Local-shift relocates a job node to a different position within a route. Since using owner-operators result in higher cost (W^k is 5 for using owner-operators' trucks), moving job nodes from routes which are served by owner-operators' trucks to routes which are served by drayage company's trucks can reduce the objective function value. Thus, in addition to the aforementioned mechanisms, a cost-reducing shift is applied to all job nodes which are served by owner-operators to check the feasibility of moving them to routes that are served by drayage company's trucks at each iteration. Note that there are two distinct differences between the cost-reducing shift process and shift process. The first is that for the shift process, since the two routes are selected randomly, the job that is moved may not come from a route that is served by owner-operators. For the cost-reducing shift, the job that is moved is guaranteed to be from a route that is served by owner-operators. The second difference is that the shift process moves only one job from one route to another, whereas the cost-reducing shift process could move more than one jobs that are served by owner-operators to routes that are served by drayage company's trucks.

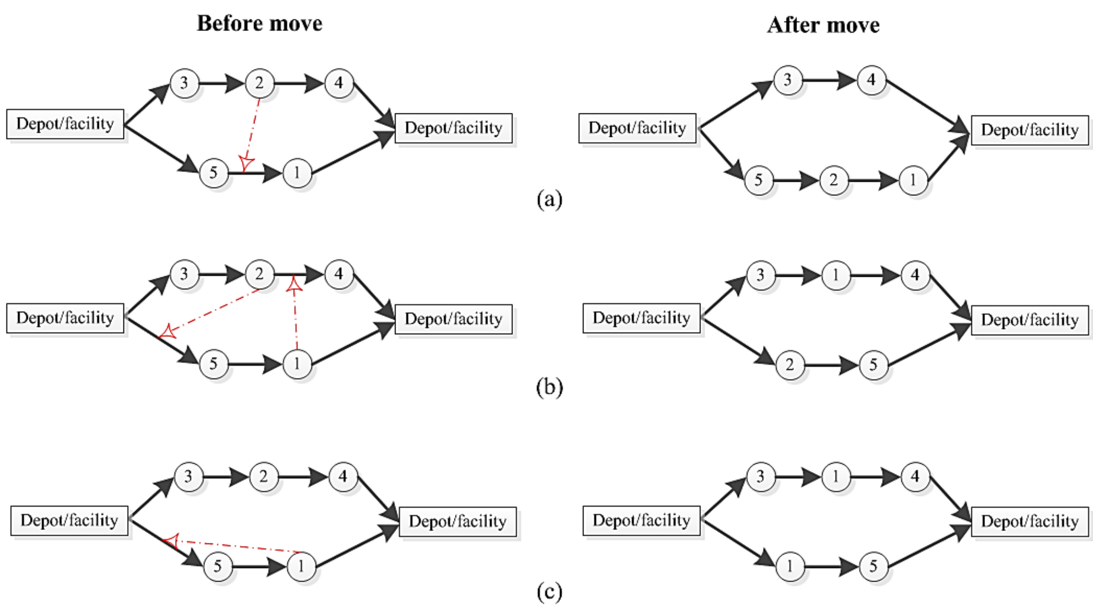


Figure 4.4 Illustration of neighborhood generation mechanism: (a) shift process; (b) interchange process; (c) local-shift process

Note that all four neighborhood generation mechanisms are applied at each iteration in the following order: (1) interchange, (2) shift, (3) local-shift and (4) cost-reducing shift. First, the interchange process generates however many neighborhood solutions are specified by the maximum neighborhood size parameter. Then, the best solution among newly generated neighborhood solutions is passed on to the shift process. The shift process in turns generates however many neighborhood solutions are specified by the maximum neighborhood size parameter. The best obtained solution from the shift process is then passed on to the local-shift process. The local-shift process is applied only to those routes which were altered by the interchange and shift processes. It checks all jobs on these routes and relocates them to a different position within the routes, if such move improves the solution. The best solution is then passed on to the cost-reducing shift process. As mentioned, the cost-reducing shift process is applied only to those jobs from routes that are served by owner-operators. The best obtained solution from this process is then passed on to the next iteration.

4.4.3 Tabu List

As mentioned, pure local search methods can get trapped in local optima. RTS prevents this by recording some attributes of performed moves in a short-term memory referred to as tabu list. In this study, the data structure used to store the tabu moves is called *TABM*, which is adopted from work of Chiang and Russell (1997). *TABM* is a matrix with n rows and v columns (n is the number of job nodes and v is the number of routes). The matrix *TABM* is initialized with high negative values. *TABM* (i,p) records the iteration number at which job node i was removed from route R_p. Suppose at iteration k, job node i is a candidate to move to the route R_p. This move is classified as tabu if:

$$k - TABM(i, p) < tt \qquad (4.22)$$

4.4.4 Reaction Mechanisms

The history of visited solutions can affect the search path in RTS algorithm. RTS tracks the frequency of revisiting solutions to adjust the search trajectory with two reaction mechanisms. These mechanisms are briefly explained below.

1. The tabu tenure is dynamically controlled using the number of iterations between repeated solutions. If a solution is repeated within a predefined number of iterations, then it means that the algorithm is falling into a cycle. In this case, the tabu tenure is increased by a predetermined factor *INC* where $INC > 1$. *tt* value increases as follows.

   $$tt = tt \times INC \tag{4.23}$$

   Moreover, a moving average of detected cycles (*moving_average*) is calculated during the search procedure. If the number of iterations passed from last change of tabu tenure is more than this moving average, then the tabu tenure is decreased by a predetermined factor *DEC* where $0 < DEC < 1$. *tt* value decreases as follows.

   $$tt = tt \times DEC \tag{4.24}$$

   Each time that the tabu tenure is updated, it is rounded up to the next integer.
2. If a solution is repeated more than *REP* times (*REP* is a predefined parameter), then that solution is considered as an often-repeated solution. If the number of often-repeated solutions is more than *CHAOS* (*CHAOS* is a predefined parameter), then it can be concluded that the search is confined to an attractor basin. In order to get out of the basin, RTS will use the escape mechanism. The escape mechanism clears the tabu list and performs successive random moves. The number of random moves is calculated using the formula proposed by (Battiti et al., 1994):

$$Number\ of\ random\ moves = 1 + (1+r) \times \frac{moving\_average}{2} \tag{4.25}$$

where:

r = a random number between 0 and 1.

To prevent the search procedure to return the same solution region, all these random moves are kept in tabu matrix. This mechanism will change the makeup of the solution and continue the search in previously unvisited solution space.

4.4.5 Termination Criteria

The developed algorithm is terminated after a certain number of iterations (step 3 of phase 2 shown in Figure 4.3) which is defined based on the size of the problem. Our algorithm is terminated after performing 25×n iterations where n is the total number of nodes.

4.5 NUMERICAL ANALYSIS

Computational experiments are conducted to test the performance of the proposed solution algorithm. An experimental design is set up to study the effect of different chassis supply models on drayage operation time, percentage of empty movement and air emissions.

The developed mathematical formulation is a mixed-integer quadratic programming model (MIQP). CPLEX was used to solve the model for smaller instances. The RTS algorithm is coded in MATLAB R2012b and used to solve larger instances. The experiments are conducted on a desktop computer with a 3.40 GHz processor and 16 GB of RAM.

4.5.1 Hypothetical Network Parameters

Two sets of experiments are performed on randomly generated instances with real life characteristics. Instances are generated on a 2-hour by 2-hour hypothetical network and the customer locations are generated randomly within the network perimeter. The first set of experiments aims to demonstrate the feasibility of the developed model and solution methodology. In this set of experiments, the network with one container terminal, one empty container depot, one chassis yard, two drayage company's truck depots and one owner-operator's facility is considered (Figure 4.5). The empty container depot and chassis yard are assumed to be located inside the terminal.

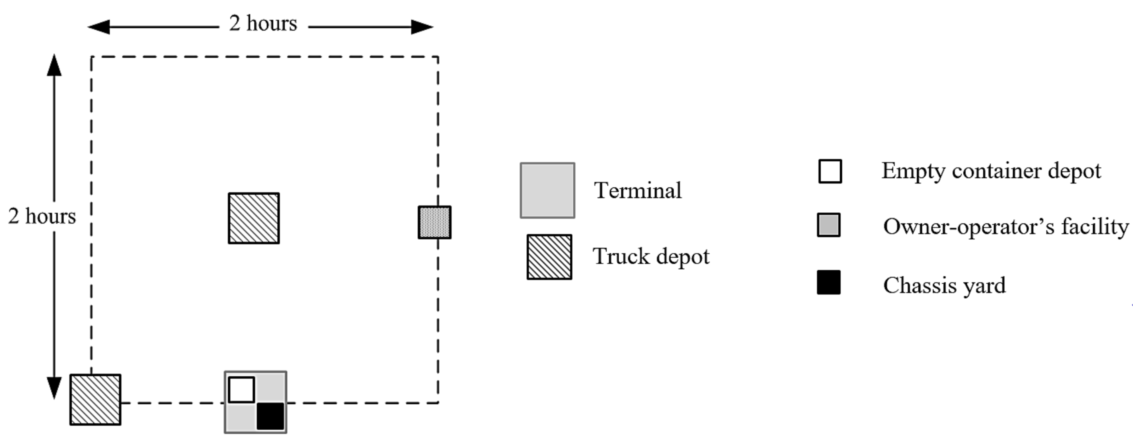


Figure 4.5 Illustration of hypothetical network

The first set of experiments is carried out using the turn time data from the Barbours Cut Container Terminal at the Port of Houston; the truck turn time is the time it takes a truck to complete a transaction at the terminal such as picking up an import container. Truck turn times by transaction types are provided in Table 4.9. For double moves (e.g. returning an empty container and picking up an import container on the same trip), the turn time is assumed to be 75% of the summed turn times. Gate queuing time at the terminal gate is assumed to be 15 minutes. The time to mount/unmount the container at customer locations is assumed to be 5 minutes (Chung et al., 2007). Packing/unpacking times are assumed to be uniformly distributed with a minimum of 5 minutes and a maximum of 60 minutes, U(5, 60) (Zhang et al., 2010). The lower bound of time windows are assumed to be uniformly distributed in the range of 0 (8:00 A.M.) to 240 (12:00 P.M.) and the upper bound is calculated according to the width of the time window. The width of the time window is assumed to be 240 minutes.

Table 4.9 Terminal turn time by transaction

Transaction type	**Turn time (min)**
Time to pick up chassis	42
Time to drop off chassis	18
Time to pick up a loaded container (import no chassis)	48
Time to pick up chassis and a loaded container (import with chassis)	60
Time to drop off a loaded container (export)	43
Time to pick up an empty container	30
Time to drop off an empty container	30

The second set of experiments aims to study the effect of different chassis supply models on drayage operation time, percentage of empty movements and air emissions. In this set of experiments, the network with one container terminal, one empty container depot, one chassis yard and one drayage company's truck depot is considered (Figure 4.6). Three different chassis yard locations are considered: (1) inside the terminal (Figures 4.6a and 4.6d), (2) outside the terminal (Figures 4.6b and 4.6e), and (3) at the motor carrier's facility (Figures 4.6c and 4.6f). In addition, two different locations are considered for the empty container depot: (1) inside the terminal (Figures 4.6a-4.6c), and (2) outside the terminal (Figures 4.6d-4.6f).

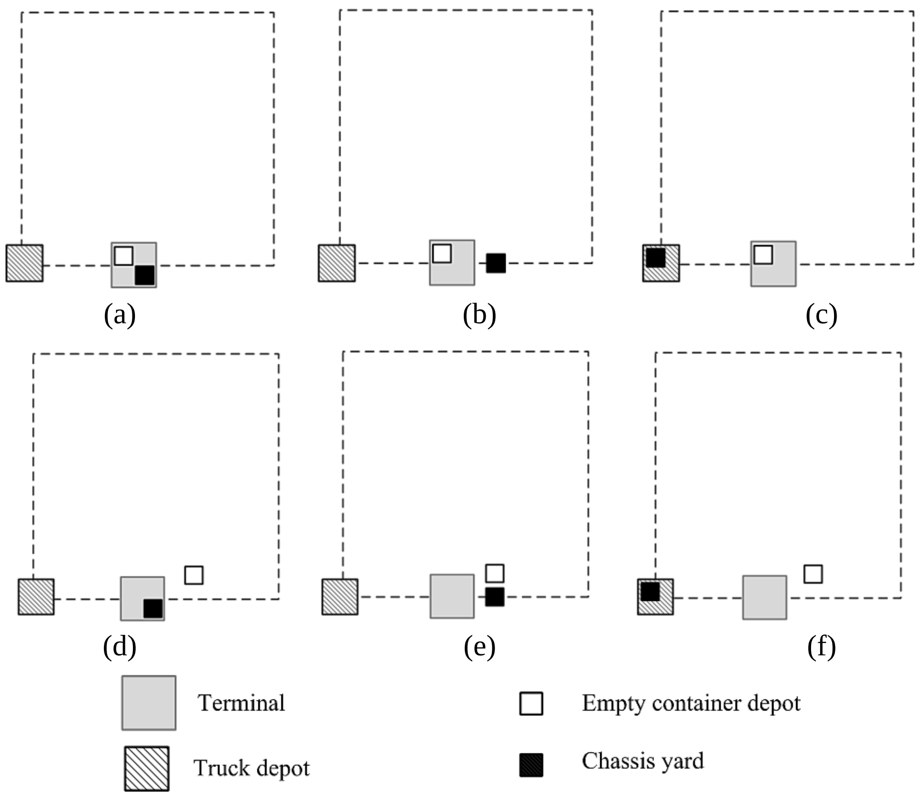


Figure 4.6 Candidate locations for chassis yard/empty container depot: (a) on-terminal/on-terminal; (b) off-terminal/on-terminal; (c) motor carrier's facility/on-terminal; (d) on-terminal/off-terminal; (e) off-terminal/off-terminal; (f) motor carrier's facility/off-terminal

In addition to the parameters used in the first set of experiments, other parameters are used in the second set. The time to drop off/pick up a chassis from an off-terminal chassis yard is assumed to be 20 minutes. It is assumed that the terminal and the off-terminal chassis yard are 10 minutes apart. It is assumed that the off-terminal chassis yard and the empty container depot are 5 minutes apart in cases where empty containers are stored outside the terminal. It is assumed that there are six different ocean carriers in the experiments involving the OC model. When jobs are created, they are randomly assigned to one of the six ocean carriers.

To evaluate the percentage of empty movements and air emissions for each instance, the proposed drayage model is first used to obtain truck routes. Then, the percentage of empty movements and air emissions are calculated from these truck routes.

4.5.2 RTS Parameters

This study used the RTS parameter values suggested by Osman and Wassan (2002) and Shiri and Huynh (2016) as a starting point. These parameters were then systematically adjusted and fine-tuned such that the RTS gives the same optimal solution as CPLEX for small-sized and some medium-sized problems. The RTS parameter values used in this work are provided in Table 4.10.

Table 4.10 RTS parameter values

Parameter	**Value**
tt	1
INC	1.1
DEC	0.8
REP	3
CHAOS	6
Maximum neighborhood size	200 for experiments 1 to 8, 1,000 for experiments 9 to 13, and 2,000 for experiments 14 to 26

4.5.3 Validation of the RTS Algorithm

A total of 28 experiments were performed to demonstrate the feasibility of the developed model and solution methodology. Instances can be classified as small, medium and large-sized problems. Table 4.11 shows a comparison of the results obtained from RTS as compared to CPLEX for small and medium-sized problems.

Table 4.11 Comparison of RTS performance against CPLEX for small and medium-sized problems

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Experiment No.	**Problem size**	**CPLEX**		**Solution method**			**Gap[1] (%)**
				Initial solution	**RTS**		
		Objective value	**Time (s)**	**Objective value**	**Objective value**	**Time (s)**	
1	2	3116	0.61	3460	3116	5.512	0
2	3	3254	0.22	3544	3254	8.254	0
3	4	1331	0.12	4086	1331	8.279	0
4	5	1349	0.27	4100	1349	11.201	0
5	6	4034	0.81	5270	4034	16.89	0
6	7	5089	0.87	7376	5089	19.870	0
7	8	7456	2.78	9051	7456	22.193	0
8	9	7640	1.28	11190	7640	19.091	0
9	10	5716	1.92	11954	5716	87.527	0
10	11	8077	6.68	11569	8077	90.046	0
11	12	8533	658.07	12358	8541	90.887	0.09
12	13	8201	7466.44	13563	8341	124.14	1.71
13	14	8895	14400.09	15235	8895	127.66	0
14	15	8740	64561.60	13844	8840	280.93	1.14
15	20	10890	96791.62	18328	11309	308.59	3.85

[1]Gap = 100 × (RTS solution - CPLEX solution)/CPLEX solution

The first column shows the experiment number. The second column shows the problem size in terms of the number of job nodes. The third and fourth columns show the objective function values and computation time of CPLEX, respectively. The fifth column shows the objective function value of the initial solution. The sixth column shows the RTS objective function value, and the seventh column shows the RTS computation time. The last column shows the gap between the CPLEX and RTS solutions. As indicated by the gap values, RTS was able to obtain the optimal solutions for the majority of the cases. The biggest gap is 3.85%. Notice that the RTS's computation time is not as affected as CPLEX by the increase in problem size. Moreover, the RTS obtains the optimal solutions a lot faster than CPLEX for larger instances; for experiment 15, the computation time of RTS is 5.14 minutes compared to 26.89 hours for CPLEX.

For large-sized problems, CPLEX runs were limited to 4 hours and the best solution obtained within this time period is reported. Table 4.12 shows the results of large-sized problems.

Table 4.12 Comparison of RTS performance against CPLEX for large-sized problems

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Experiment No.	**Problem size**	**CPLEX**	**Solution method**			**Gap[1] (%)**
			Initial solution	**RTS**		
		Objective value	**Objective value**	**Objective value**	**Time (s)**	
16	30	10688	18750	9885	362.10	-7.51
17	35	13702	23379	10909	379.32	-20.38
18	40	11002	24302	9963	410.13	-9.44
19	45	13393	23271	12261	495.34	-8.45
20	50	37605	47409	26922	576.653	-28.41
21	55	38208	51738	21702	425.575	-43.20
22	60	45862	56266	26806	486.991	-41.55
23	70	49062	57336	25896	550.13	-47.22
24	80	N/A	70383	29446	647.78	N/A
25	90	N/A	80038	35783	631.71	N/A
26	100	N/A	86900	46536	744.25	N/A
27	120	N/A	100772	59789	765.1	N/A
28	150	N/A	133079	68718	800.15	N/A

The first column of Table 4.12 shows the experiment number. The second column shows the problem size in terms of the number of job nodes. The CPLEX incumbent solution at the end of the 4-hour run is reported in the third column. An “N/A” in the third column indicates that CPLEX was not able to obtain a solution. The results obtained from the developed solution methodology (RTS) are reported in the fourth, fifth and sixth columns. The fourth column shows the objective function value of the initial solution. The fifth column shows the RTS objective function value, and the sixth column shows the RTS computation time. The last column shows the gap between the CPLEX and RTS solutions. As shown in the column 7, for experiments 16 to 23 the gap values are negative, which indicates that RTS obtains better (lower) objective function than CPLEX. For experiments 24 to 28 CPLEX was not able to give a solution while RTS yields a solution within a reasonable time. These results demonstrate that RTS can be used to obtain optimal or near-optimal solutions for the drayage problem in an acceptable time.

4.5.4 Analysis of RTS Performance

In this section, the effect of the RTS parameters, particularly the total number of iterations and maximum neighborhood size, on solution quality and computation time is investigated. In Table 4.11, a maximum gap of 3.85% is reported; however, this gap can be reduced if we increase the total number of iterations and maximum neighborhood size at the expense of computation time. To understand this tradeoff and how the total number of iterations and maximum neighborhood size affect solution quality, experiments 1 to 15 shown in Table 4.11 is rerun with these two parameters changed as follows.

RTS₁: Maximum neighborhood size is doubled (from 200 to 400 for experiments 29 to 36, from 1,000 to 2,000 for experiments 37 to 41, and from 2,000 to 4,000 for experiments 42 to 43).

RTS₂: Total number of iterations is increased from 25×n to 50×n.

The results are summarized in Table 4.13.

Table 4.13 The effect of increase in the total number of iterations and maximum neighborhood size on solution quality

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Experiment No.	**Problem size**	**Objective value**	**Time (s)**	**Gap (%)**	**Objective value**	**Time (s)**	**Gap (%)**
29	2	3116	8.40	0	3116	8.19	0
30	3	3254	12.19	0	3254	12.30	0
31	4	1331	16.05	0	1331	19.69	0
32	5	1349	22.18	0	1349	22.41	0
33	6	4034	30.58	0	4034	35.36	0
34	7	5089	26.88	0	5089	32.90	0
35	8	7456	41.01	0	7456	41.19	0
36	9	7640	43.64	0	7640	51.72	0
37	10	5716	168.36	0	5716	166.807	0
38	11	8077	249.23	0	8077	258.90	0
39	12	8533	272.69	0	8533	313.75	0
40	13	8201	223.12	0	8201	249.77	0
41	14	8895	249.74	0	8895	311.45	0
42	15	8740	557.90	0	8740	569.79	0
43	20	10952	742.25	0.57	11028	729.31	1.27

The first column of Table 4.13 shows the experiment number; experiment 29 corresponds to experiment 1 in Table 4.11 and experiment 43 corresponds to experiment 15 in Table 4.11. The second column shows the problem size in terms of the number of job nodes. The third column shows the objective function value obtained using the RTS_1 values. The fourth column shows the corresponding computation time. The fifth column shows the gap between the obtained CPLEX solutions in Table 4.11 and RTS_1 solutions. The last three columns show the same information as columns 3, 4, and 5, but for solutions obtained using RTS_2 values. As shown in columns 5 and 8, the gaps are lower compared to the results shown in Table 4.11, but the computation time is higher. Between RTS_1 and RTS_2, both generated the same objective function values, except for the experiment 43 where RTS_1 yields a lower value (and hence a lower gap). In terms of computation time, RTS_1 yields a lower computation time than RTS_2 in 12 out of 15 experiments. These findings suggest that increasing the maximum neighborhood size is more effective than increasing the total number of iterations.

4.5.5 Experimental Design

An experimental design is set up to study the effect of different chassis supply models on drayage operation time, air emissions and percentage of empty movements. Design of experiments (DOE) is an objective investigation process which designs sets of experiments to draw a valid conclusion from an experimental study effectively and efficiently (Montgomery, 2008). DOE involves designing systematic change in inputs in order to reduce or remove experimental bias and study how output varies accordingly (Antony, 2014). DOE has found broad applications and has been applied in nearly all fields such as engineering, science and even in marketing. In DOE, the term "factor" refers to variables that are chosen to be studied. They are systematically set to predefined discrete values, known as "levels." One type of DOE is factorial experimental design (FED). This method is often used when there are several factors involved (Montgomery, 2008). In FED, combinations of all levels of factors are considered, and then the effect of each combination on output is studied. In this work, the FED is used to examine the effect of U.S. chassis supply models on drayage operation time, air emissions and percentage of empty movement.

In this study, the factors considered, and their levels are as follows.

Factors and levels

1. Empty container depot location (ECL)

   Levels: (1) the empty container depot is located inside the terminal (ONEC), and (2) the empty container depot is located outside the terminal (OFFEC)

2. Chassis yard location (CHSS)

   Levels: (1) the chassis yard is located inside the terminal in COOP, RONT and T models (ONTP), (2) the chassis yard is located inside the terminal in the OC model (ONTO), (3) the chassis yard is located outside the terminal in ROFFT (OFFTP), and (4) the chassis yard is located at motor carrier's facility in MC model (MCF)

3. Problem size in terms of number of job nodes (PS)

   Levels: (1) 60, and (2) 100

4. The ratio of import containers to export containers (IER)

   Levels: (1) 70:30, (2) 60:40, and (3) 40:60

5. The ratio of 20-ft containers to 40-ft containers (CSR)

   Levels: (1) 20:80, (2) 25:75, and (3) 40:60

The 60:40 IER is chosen to reflect the current import to export ratio in the U.S. (U.S. Census Bureau). It serves as the base ratio. The other two ratios are selected to reflect future possible scenarios where the U.S. would become even more import dependent (70:30) or the export dominant (40:60). The 25:75 CSR is chosen to reflect the current 20-ft to 40-ft container ratio in the U.S. (NCFRP Report 20). It serves as the base ratio. The other two ratios are selected to reflect other possible scenarios.

The combination of factors and levels result in a 2×4×2×3×3 factorial design which yields a total of 144 problem classes, as shown in Table 4.14. For each problem class, three instances are randomly generated using the characteristics of that class. Thus, there is a total of 432 problem instances.

To facilitate the presentation of the results, the combination of factors (4 and 5) and their levels are grouped into subclasses, as outlined below. Note that the results are grouped by their subclasses; however, the results are discussed according their classes.

Subclasses

Subclass 1. 70:30 *and* 20:80

Subclass 2. 70:30 *and* 25:75

Subclass 3. 70:30 *and* 40:60

Subclass 4. 60:40 *and* 20:80

Subclass 5. 60:40 *and* 25:75

Subclass 6. 60:40 *and* 40:60

Subclass 7. 40:60 *and* 20:80

Subclass 8. 40:60 *and* 25:75

Subclass 9. 40:60 *and* 40:60

Table 4.14 Description of problem classes

Class	ECL	CHSS	PS	IER	CSR	Class	ECL	CHSS	PS	IER	CSR	Class	ECL	CHSS	PS	IER	CSR	Class	ECL	CHSS	PS	IER	CSR
1	ONEC	ONTP	60	70:30	20:80	**37**	ONEC	OFFTP	60	70:30	20:80	**73**	OFFEC	ONTP	60	70:30	20:80	**109**	OFFEC	OFFTP	60	70:30	20:80
2	ONEC	ONTP	60	70:30	25:75	**38**	ONEC	OFFTP	60	70:30	25:75	**74**	OFFEC	ONTP	60	70:30	25:75	**110**	OFFEC	OFFTP	60	70:30	25:75
3	ONEC	ONTP	60	70:30	40:60	**39**	ONEC	OFFTP	60	70:30	40:60	**75**	OFFEC	ONTP	60	70:30	40:60	**111**	OFFEC	OFFTP	60	70:30	40:60
4	ONEC	ONTP	60	60:40	20:80	**10**	ONEC	OFFTP	60	60:40	20:80	**76**	OFFEC	ONTP	60	60:40	20:80	**112**	OFFEC	OFFTP	60	60:40	20:80
5	ONEC	ONTP	60	60:40	25:75	**41**	ONEC	OFFTP	60	60:40	25:75	**77**	OFFEC	ONTP	60	60:40	25:75	**113**	OFFEC	OFFTP	60	60:40	25:75
6	ONEC	ONTP	60	60:40	40:60	**42**	ONEC	OFFTP	60	60:40	40:60	**78**	OFFEC	ONTP	60	60:40	40:60	**114**	OFFEC	OFFTP	60	60:40	40:60
7	ONEC	ONTP	60	40:60	20:80	**43**	ONEC	OFFTP	60	40:60	20:80	**79**	OFFEC	ONTP	60	40:60	20:80	**115**	OFFEC	OFFTP	60	40:60	20:80
8	ONEC	ONTP	60	40:60	25:75	**44**	ONEC	OFFTP	60	40:60	25:75	**80**	OFFEC	ONTP	60	40:60	25:75	**116**	OFFEC	OFFTP	60	40:60	25:75
9	ONEC	ONTP	60	40:60	40:60	**45**	ONEC	OFFTP	60	40:60	40:60	**81**	OFFEC	ONTP	60	40:60	40:60	**117**	OFFEC	OFFTP	60	40:60	40:60
10	ONEC	ONTP	100	70:30	20:80	**46**	ONEC	OFFTP	100	70:30	20:80	**82**	OFFEC	ONTP	100	70:30	20:80	**118**	OFFEC	OFFTP	100	70:30	20:80
11	ONEC	ONTP	100	70:30	25:75	**47**	ONEC	OFFTP	100	70:30	25:75	**83**	OFFEC	ONTP	100	70:30	25:75	**119**	OFFEC	OFFTP	100	70:30	25:75
12	ONEC	ONTP	100	70:30	40:60	**48**	ONEC	OFFTP	100	70:30	40:60	**84**	OFFEC	ONTP	100	70:30	40:60	**120**	OFFEC	OFFTP	100	70:30	40:60
13	ONEC	ONTP	100	60:40	20:80	**49**	ONEC	OFFTP	100	60:40	20:80	**85**	OFFEC	ONTP	100	60:40	20:80	**121**	OFFEC	OFFTP	100	60:40	20:80
14	ONEC	ONTP	100	60:40	25:75	**50**	ONEC	OFFTP	100	60:40	25:75	**86**	OFFEC	ONTP	100	60:40	25:75	**122**	OFFEC	OFFTP	100	60:40	25:75
15	ONEC	ONTP	100	60:40	40:60	**51**	ONEC	OFFTP	100	60:40	40:60	**87**	OFFEC	ONTP	100	60:40	40:60	**123**	OFFEC	OFFTP	100	60:40	40:60
16	ONEC	ONTP	100	40:60	20:80	**52**	ONEC	OFFTP	100	40:60	20:80	**88**	OFFEC	ONTP	100	40:60	20:80	**124**	OFFEC	OFFTP	100	40:60	20:80
17	ONEC	ONTP	100	40:60	25:75	**53**	ONEC	OFFTP	100	40:60	25:75	**89**	OFFEC	ONTP	100	40:60	25:75	**125**	OFFEC	OFFTP	100	40:60	25:75
18	ONEC	ONTP	100	40:60	40:60	**54**	ONEC	OFFTP	100	40:60	40:60	**90**	OFFEC	ONTP	100	40:60	40:60	**126**	OFFEC	OFFTP	100	40:60	40:60
19	ONEC	ONTO	60	70:30	20:80	**55**	ONEC	MCF	60	70:30	20:80	**91**	OFFEC	ONTO	60	70:30	20:80	**127**	OFFEC	MCF	60	70:30	20:80
20	ONEC	ONTO	60	70:30	25:75	**56**	ONEC	MCF	60	70:30	25:75	**92**	OFFEC	ONTO	60	70:30	25:75	**128**	OFFEC	MCF	60	70:30	25:75
21	ONEC	ONTO	60	70:30	40:60	**57**	ONEC	MCF	60	70:30	40:60	**93**	OFFEC	ONTO	60	70:30	40:60	**129**	OFFEC	MCF	60	70:30	40:60
22	ONEC	ONTO	60	60:40	20:80	**58**	ONEC	MCF	60	60:40	20:80	**94**	OFFEC	ONTO	60	60:40	20:80	**130**	OFFEC	MCF	60	60:40	20:80
23	ONEC	ONTO	60	60:40	25:75	**59**	ONEC	MCF	60	60:40	25:75	**95**	OFFEC	ONTO	60	60:40	25:75	**131**	OFFEC	MCF	60	60:40	25:75
24	ONEC	ONTO	60	60:40	40:60	**60**	ONEC	MCF	60	60:40	40:60	**96**	OFFEC	ONTO	60	60:40	40:60	**132**	OFFEC	MCF	60	60:40	40:60
25	ONEC	ONTO	60	40:60	20:80	**61**	ONEC	MCF	60	40:60	20:80	**97**	OFFEC	ONTO	60	40:60	20:80	**133**	OFFEC	MCF	60	40:60	20:80
26	ONEC	ONTO	60	40:60	25:75	**62**	ONEC	MCF	60	40:60	25:75	**98**	OFFEC	ONTO	60	40:60	25:75	**134**	OFFEC	MCF	60	40:60	25:75
27	ONEC	ONTO	60	40:60	40:60	**63**	ONEC	MCF	60	40:60	40:60	**99**	OFFEC	ONTO	60	40:60	40:60	**135**	OFFEC	MCF	60	40:60	40:60
28	ONEC	ONTO	100	70:30	20:80	**64**	ONEC	MCF	100	70:30	20:80	**100**	OFFEC	ONTO	100	70:30	20:80	**136**	OFFEC	MCF	100	70:30	20:80
29	ONEC	ONTO	100	70:30	25:75	**65**	ONEC	MCF	100	70:30	25:75	**101**	OFFEC	ONTO	100	70:30	25:75	**137**	OFFEC	MCF	100	70:30	25:75
30	ONEC	ONTO	100	70:30	40:60	**66**	ONEC	MCF	100	70:30	40:60	**102**	OFFEC	ONTO	100	70:30	40:60	**138**	OFFEC	MCF	100	70:30	40:60
31	ONEC	ONTO	100	60:40	20:80	**67**	ONEC	MCF	100	60:40	20:80	**103**	OFFEC	ONTO	100	60:40	20:80	**139**	OFFEC	MCF	100	60:40	20:80
32	ONEC	ONTO	100	60:40	25:75	**68**	ONEC	MCF	100	60:40	25:75	**104**	OFFEC	ONTO	100	60:40	25:75	**140**	OFFEC	MCF	100	60:40	25:75
33	ONEC	ONTO	100	60:40	40:60	**69**	ONEC	MCF	100	60:40	40:60	**105**	OFFEC	ONTO	100	60:40	40:60	**141**	OFFEC	MCF	100	60:40	40:60
34	ONEC	ONTO	100	40:60	20:80	**70**	ONEC	MCF	100	40:60	20:80	**106**	OFFEC	ONTO	100	40:60	20:80	**142**	OFFEC	MCF	100	40:60	20:80
35	ONEC	ONTO	100	40:60	25:75	**71**	ONEC	MCF	100	40:60	25:75	**107**	OFFEC	ONTO	100	40:60	25:75	**143**	OFFEC	MCF	100	40:60	25:75
36	ONEC	ONTO	100	40:60	40:60	**72**	ONEC	MCF	100	40:60	40:60	**108**	OFFEC	ONTO	100	40:60	40:60	**144**	OFFEC	MCF	100	40:60	40:60

4.5.6 Drayage Operation Time

Figure 4.7 shows how the drayage operation time differs for different U.S. chassis supply models based on the location of the chassis yard. The results are divided into four groups by problem size in terms of the number of job nodes (PS) and empty container depot location (ECL). Figures 4.7a and 4.7b show the results for classes where the empty container depot is located inside the terminal (ONEC) and with 60 and 100 job nodes, respectively. Figures 4.7c and 4.7d show the results of classes where the empty container depot is located outside the terminal (OFFEC) and with 60 and 100 job nodes, respectively. The results indicate that the CHSS level has an effect on drayage operation time. In particular, the drayage operation time increases as the CHSS level changes in this order: ONTP→MCF →ONTO→OFFTP. The results suggest that drayage operation time increases as the chassis supply model is changed in this order: COOP/RONT/T→MC→OC→ROFFT. These results correspond to intuition because when chassis are stored inside the terminal, trucks can pick up chassis and loaded containers (and also empty container when the empty container depot is located inside the terminal) on the same trip to the terminal. The reduction in the number of truck trips to the terminal leads to a reduction in drayage operation time.

The results show that in going from the OC model to one of the COOP, RONT, T and MC models, drayage operation efficiency would increase, whereas in going from the OC model to the ROFFP model drayage operation efficiency would decrease. The difference in drayage operation time between using the ocean carrier model and alternative models are as follows. In going from the OC model (ONTO) to one of the COOP, RONT and T models (ONTP), drayage operation time decreased by 5.38% in classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC) and drayage operation time decreased by 4.31% on average in classes with 100 job nodes where the empty container depot is located inside the terminal (ONEC). In this transition, the drayage operation time decreased by 4.94% on average in classes with 60 job nodes where the empty container depot is located outside the terminal (OFFEC) and drayage operation time decreased by 5.17% on average in classes with 100 job nodes where the empty container depot is located outside the terminal. In going from the OC model (ONTO) to the ROFFT model (OFFTP), drayage operation time increased by 5.28% on average in classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC) and drayage operation time increased by 5.90% on average in classes with 100 job nodes where the empty container depot is located inside the terminal (ONEC). For this transition, the drayage operation time increased by 1.66% on average in classes with 60 job nodes where the empty container depot is located outside the terminal (OFFEC) and increased by 1.76% on average in classes with 100 job nodes where the empty container depot is located outside the terminal (OFFEC). In going from the OC model (ONTO) to the MC model (MCF), the drayage operation time decreased by 1.9% on average in classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC) and drayage operation time decreased by 0.93% on average in classes with 100 job nodes where the empty container depot is located inside the terminal (ONEC). For this transition, the drayage operation time decreased by 3.49% on average in classes with 60 job nodes where the empty container depot is located outside the terminal (OFFEC) and drayage operation time decreased by 3.57% on average in classes with 100 job nodes where the empty container depot is located outside the terminal (OFFEC).

In the OC model (ONTO) as well as COOP, RONT and T models (ONTP) chassis are provided inside the terminal and trucks can utilize the mentioned benefit of double moves. However, COOP, RONT and T models have the lowest operation time, whereas OC model has the second-highest operation time. The reason is because since chassis and containers are owned and provided by the ocean carrier in the OC model, there is less opportunity to use chassis and container for multiple jobs.

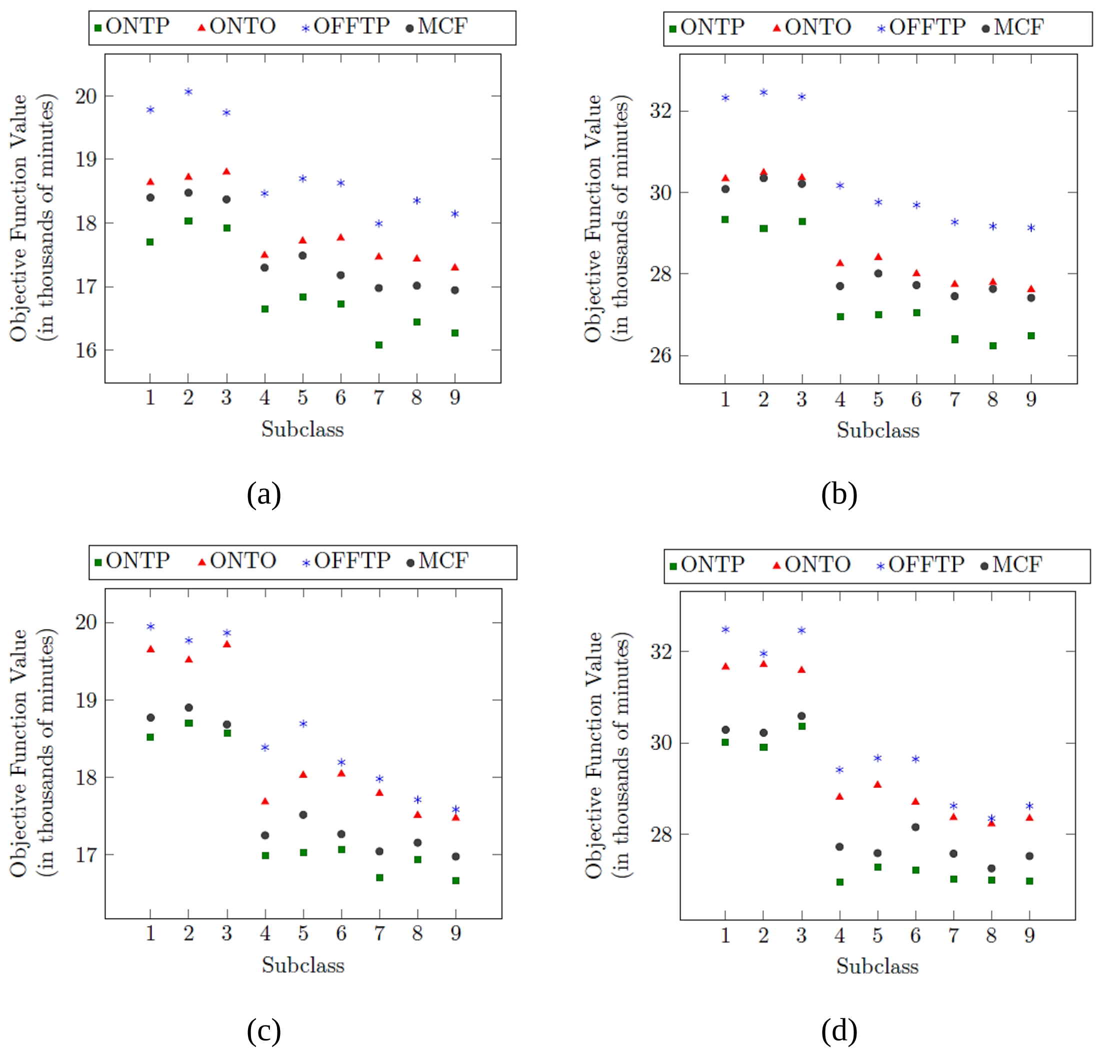


Figure 4.7 Average drayage operation time by subclasses according to level of ECL/level of PS: (a) ONEC/60; (b) ONEC/100; (c) OFFEC/60; (d) OFFEC/100

In both the ROFFT model (OFFTP) and MC model (MCF) the chassis yard is located outside the terminal. The ROFFT model has the highest operation time while the MC model has the third-highest operation time between all chassis models. As mentioned, in cases that the chassis yard is located outside the terminal, trucks should pick up the empty/loaded container and chassis from different locations which increases drayage operation time. It was expected that the closer the chassis yard is to the terminal the more efficient drayage operation will be; however, that is not the case. The reason that the MC model yields better results than the ROFFT model is because with chassis being stored at the motor carrier facility (which is assumed to be the truck depot here), all trucks save two trip legs in each route; one at the beginning of the route from the truck depot to the chassis yard to pick up chassis and another at the end of their route from the final job location to the chassis yard to drop off the chassis. It can be generalized from these results that it is better for a drayage company to store their chassis in their truck depot rather than at a separate location near the terminal.

Comparing the results of those classes where the empty container depot is located inside the terminal (ONEC) against those classes where the empty container depot is located outside the terminal (OFFEC) they indicate that only the ROFFT model (OFFTP where chassis is provided in the chassis yard outside the terminal) can improve drayage productivity. In summary, when moving the empty container depot from inside the terminal to outside the terminal, the average change in the drayage operation time is a 2.96% increase in the COOP, RONT and T models (ONTP), 2.49% increase in the OC model (ONTO), 0.89% increase in the MC model (MCF) and 1.04% decrease in the ROFFT model (OFFTP) in classes with 60 job nodes. Also, when moving the empty container depot from inside the terminal to outside the terminal, the average change in the drayage operation time is a 1.97% increase in the COOP, RONT and T models (ONTP), 2.89% increase in the OC model (ONTO), 0.15% increase in the MC model (MCF) and 1.15% decrease in the ROFFT model (OFFTP) in classes with 100 job nodes. According to these results, it can be concluded that the location of the chassis yard and empty container depot have an important effect on drayage operation and the optimal location of the empty container depot depends on the chassis supply model.

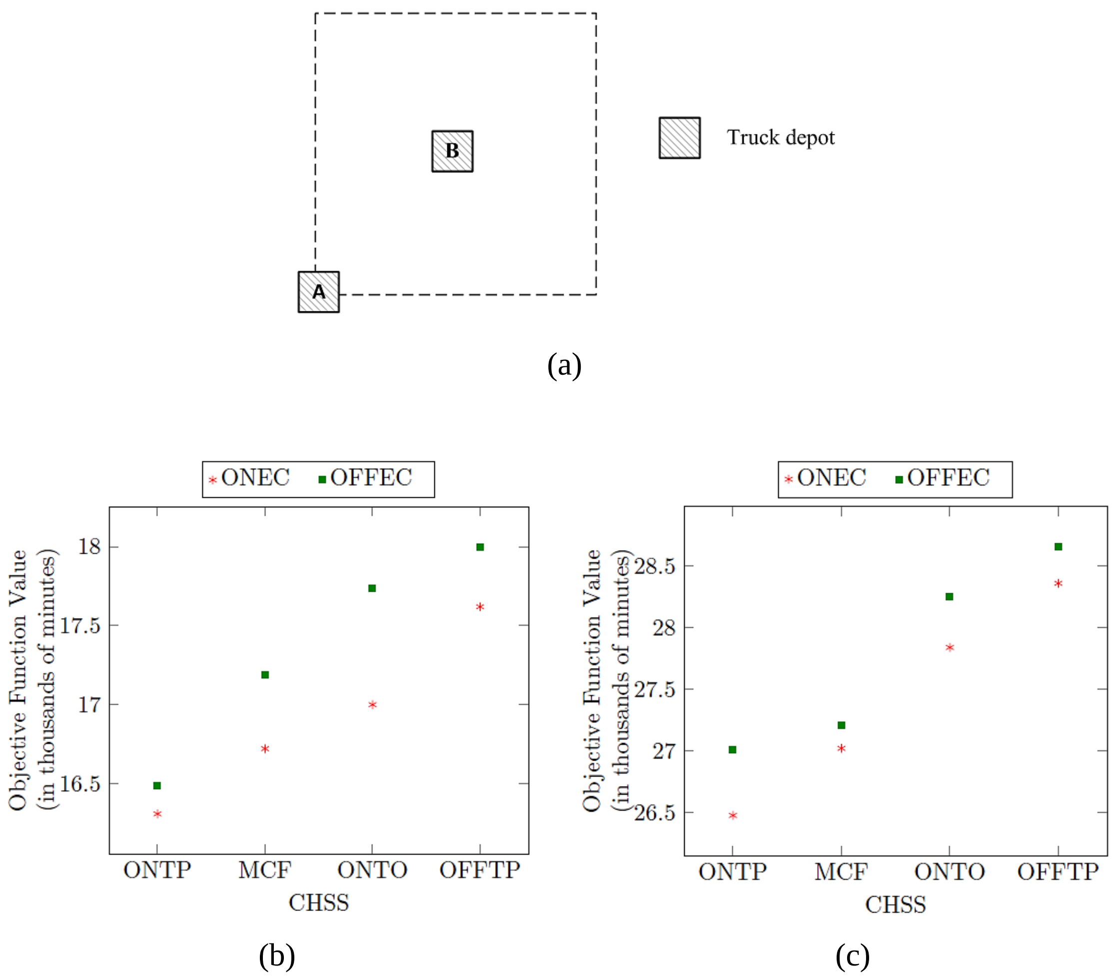


Figure 4.8 (a) Candidate locations for the truck depot; (b) Average drayage operation time for classes with 60 job nodes; (c) Average drayage operation time for classes with 100 job nodes

To examine the effect of the truck depot location, another set of experiments is conducted. As shown in Figure 4.8a, the depot location shown in Figure 4.6 is moved from location A to location B. Location B is in the middle of the network and is closer to customer locations. For this set of experiments, only classes with factors 4 and 5 at their base ratios are considered (i.e., classes 5, 14, 23, 32, 41, 50, 59, 68, 77, 86, 95, 104, 113, 122, 131 and 140). Figures 4.8b and 4.8c show the results for classes with 60 and 100 job nodes, respectively. The results indicate that the depot location does not affect the relative ranking of the different chassis supply models. The drayage operation time increases as the CHSS level changes in this order: ONTP→MCF →ONTO→OFFTP when the truck depot is at location B.

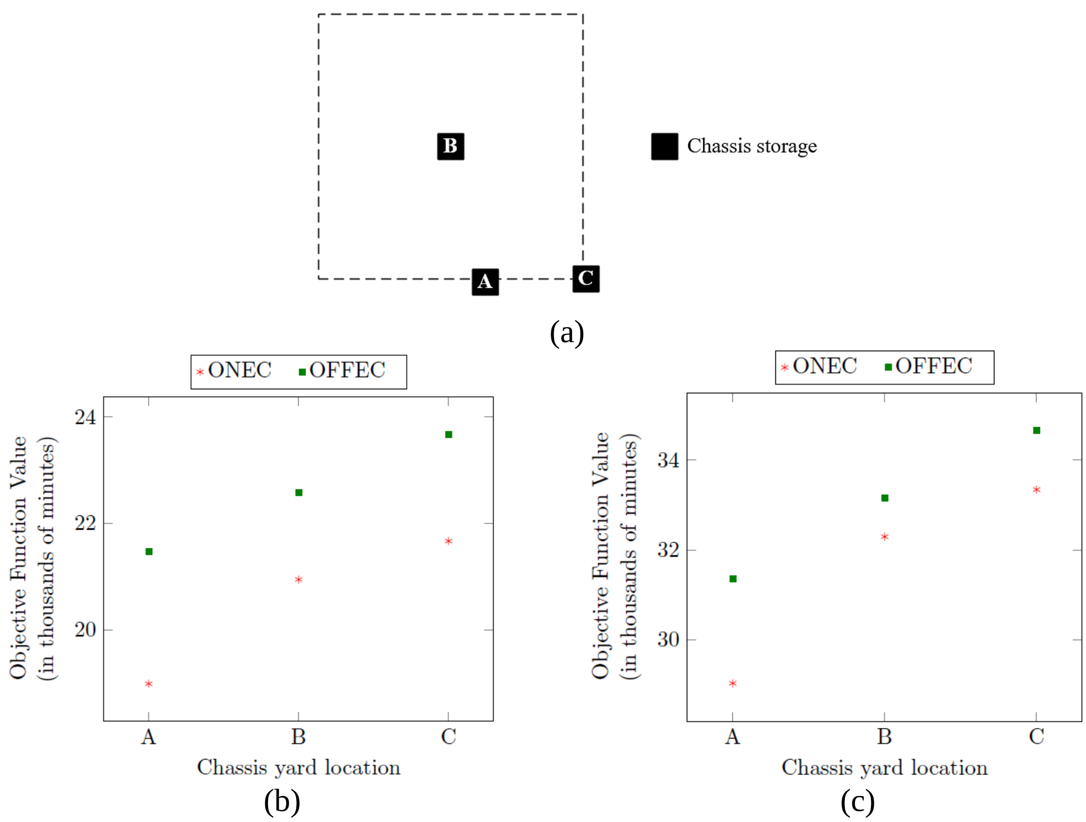


Figure 4.9 (a) Candidate location for chassis yard; (b) Average drayage operation time for classes with 60 job nodes; (c) Average drayage operation time for classes with for classes with 100 job nodes

In another set of experiments, the effect of the chassis yard location when it is located outside the terminal (OFFTP) on drayage operation time is investigated. As depicted in Figure 4.9a, the chassis yard location shown in Figures 4.6b and 4.6e is moved from location A to location B and location C. Location A is closer to the terminal than locations B and C. Locations B and C both have the same travel time to the terminal, but location B is closer to the truck depot and customer locations. For this set of experiments, only classes that pertain to OFFTP and with factors 4 and 5 at their base ratios are considered (i.e., classes 41, 50, 113 and 122). Figures 4.9b and 4.9c show the results for classes with 60 and 100 job nodes, respectively. It can be seen in Figures 4.9b and 4.9c that when changing the chassis yard location from A to C, the drayage operation time is increased by 14.11% on average for classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC) and the drayage operation time is increased by 14.87% on average for classes with 100 job nodes where the empty container depot is located inside the terminal. Also, when changing the chassis yard location from A to C the drayage operation time is increased by 10.26% on average for class with 60 job nodes where the empty container depot is located outside the terminal (OFFEC) and the drayage operation time is increased by 10.53% on average for classes with 100 job nodes where the empty container depot is located outside the terminal. These findings suggest that locating a chassis yard closer to the terminal will benefit drayage operations. Furthermore, chassis yard at location B resulted in lower drayage operation time than at location C. This result makes sense since all routes have the depot-to-chassis yard segment, and vice versa; thus, the closer they are together the more beneficial it is for drayage operations. It can be generalized from these results that the location of the chassis yard has an effect on drayage operation time; specifically, the closer it is to the terminal and truck depot the better.

4.5.7 Percentage of Empty Movement

One of the utilization factors to evaluate the efficiency of drayage operations is the number or percentage of empty movements (i.e. truck trips without a loaded container). Empty movements include movements of tractor, bare chassis and empty container. Empty movements do not directly contribute to the profit of a drayage company, but it is essential to its continuing operations. To maximize the profitability of drayage operation, non-revenue generating empty movements should be minimized as much as possible.

Figure 4.10 shows the percentage of empty movements. The results indicate that the percentage of empty movements increases as the CHSS level changes in this order: ONTP→MCF →ONTO→OFFTP. Thus, it suggests that the percentage of empty movements increases as the chassis supply model is changed in this order: COOP/RONT/T→MC→OC→ROFFT. For example, when moving the location of the chassis yard from outside the terminal (ROFFT model) to inside the terminal (COOP, RONT and T models), the percentage of empty movements decreased by 9.99% on average in classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC) and decreased by 8.42% on average in classes with 100 job nodes where the empty container depot is located inside the terminal (ONEC). Also, when moving the location of the chassis yard from outside the terminal (ROFFT model) to inside the terminal (COOP, RONT and T models), the percentage of empty movements is decreased by 4.77% on average for classes with 60 job nodes where the empty container depot is located outside the terminal (OFFEC) and is decreased by 3.33% on average for classes with 100 job nodes where the empty container depot is located outside the terminal (OFFEC). These results correspond to intuition because when chassis are stored outside the terminal, trucks need to pick up chassis and loaded/empty containers from different locations which add empty movements to truck trips and consequently increases the percentage of empty movements.

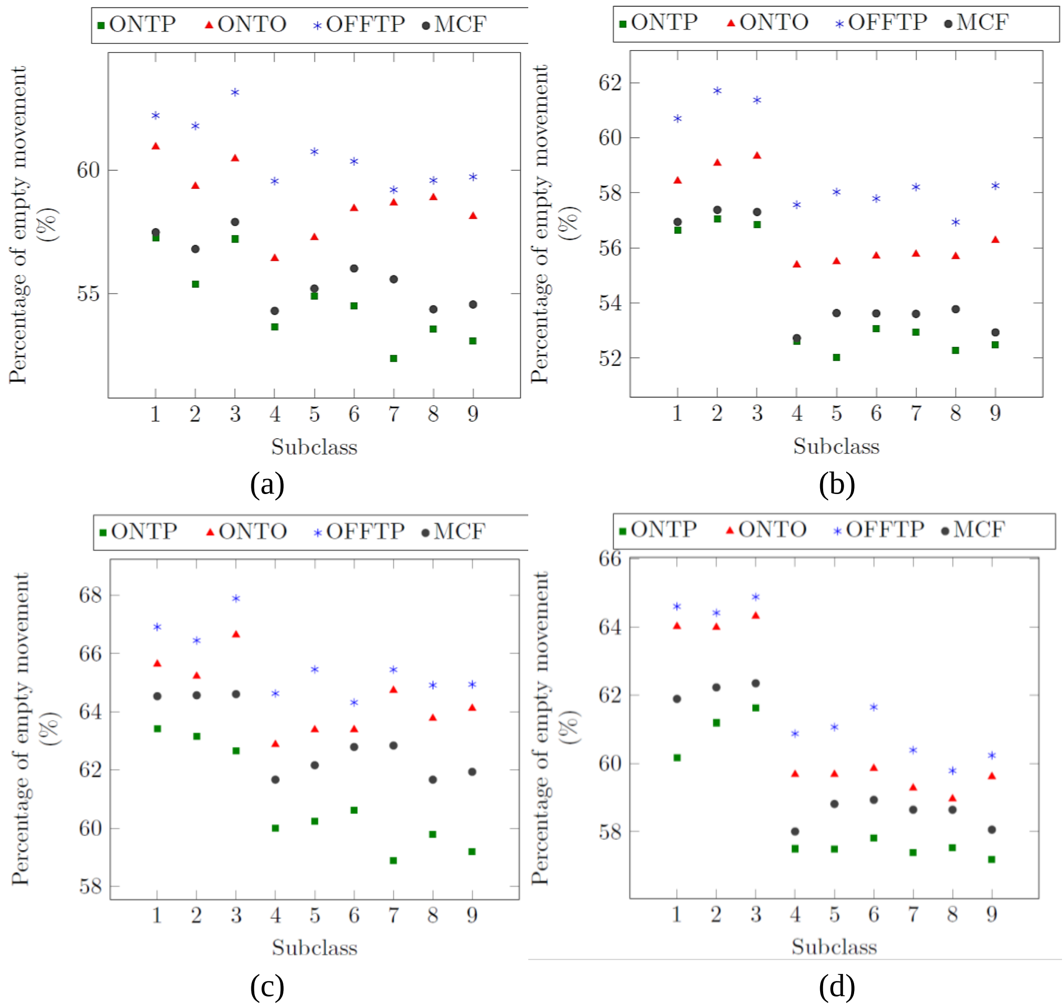


Figure 4.10 Percentage of empty movements by sub classes according to level of ECL/level of PS: (a) ONEC/60; (b) ONEC/100; (c) OFFEC/60; (d) OFFEC/100

4.5.8 On-Road Emission

The MEET model was used to calculate the air emissions. The CO, CO_2, VOC, NO_X and PM pollutants for all chassis supply models are presented in Figures 4.11a- 4.11t.

The results indicate that OFFTP yields the highest total mass of emissions whereas ONTP yields the lowest. Thus, the relative ranking of chassis supply models in terms total mass of air emissions from lower to higher are: (1) COOP, RONT and T models, (2) MC model, (3) OC model, and (4) ROFFT model. For instance, in going from one of the COOP, RONT and T models to the ROFFT model, CO emissions increased by 14.15% on average, CO_2 emissions increased by 13.35% on average, VOC emissions increased by 15.13% on average, NO_X emissions increased by 13.59% on average, and PM emissions increased by 14.22% on average in classes with 60 job nodes where the empty container depot is located inside the terminal (ONEC). Also, for this transition, CO emissions increased by 11.07% on average, CO2 emissions increased by 10.47% on average, VOC emissions increased by 11.85% on average, NO_X emissions increased by 10.65% on average, and PM emissions increased by 11.11% on average in the classes with 100 job nodes where the empty container depot is located inside the terminal (ONEC). Also, in going from one of the COOP, RONT and T models to the ROFFT model, CO emissions increased by 9.28% on average, CO_2 emissions increased by 16.98% on average, VOC emissions increased by 6.83% on average, NO_X emissions increased by 15.88% on average, and PM emissions increased by 10.74% on average in classes with 60 job nodes where the empty container depot is located outside the terminal (OFFEC). Also, for this transition, CO emissions increased by 10.46% on average, CO2 emissions increased by 12.23% on average, VOC emissions increased by 13.41% on average, NO_X emissions increased by 8.85% on average, and PM emissions increased by 10.74% on average in the classes with 100 job nodes where the empty container depot is located outside the terminal (OFFEC). These results indicate that the COOP, RONT and T models will result in less on-road emissions.

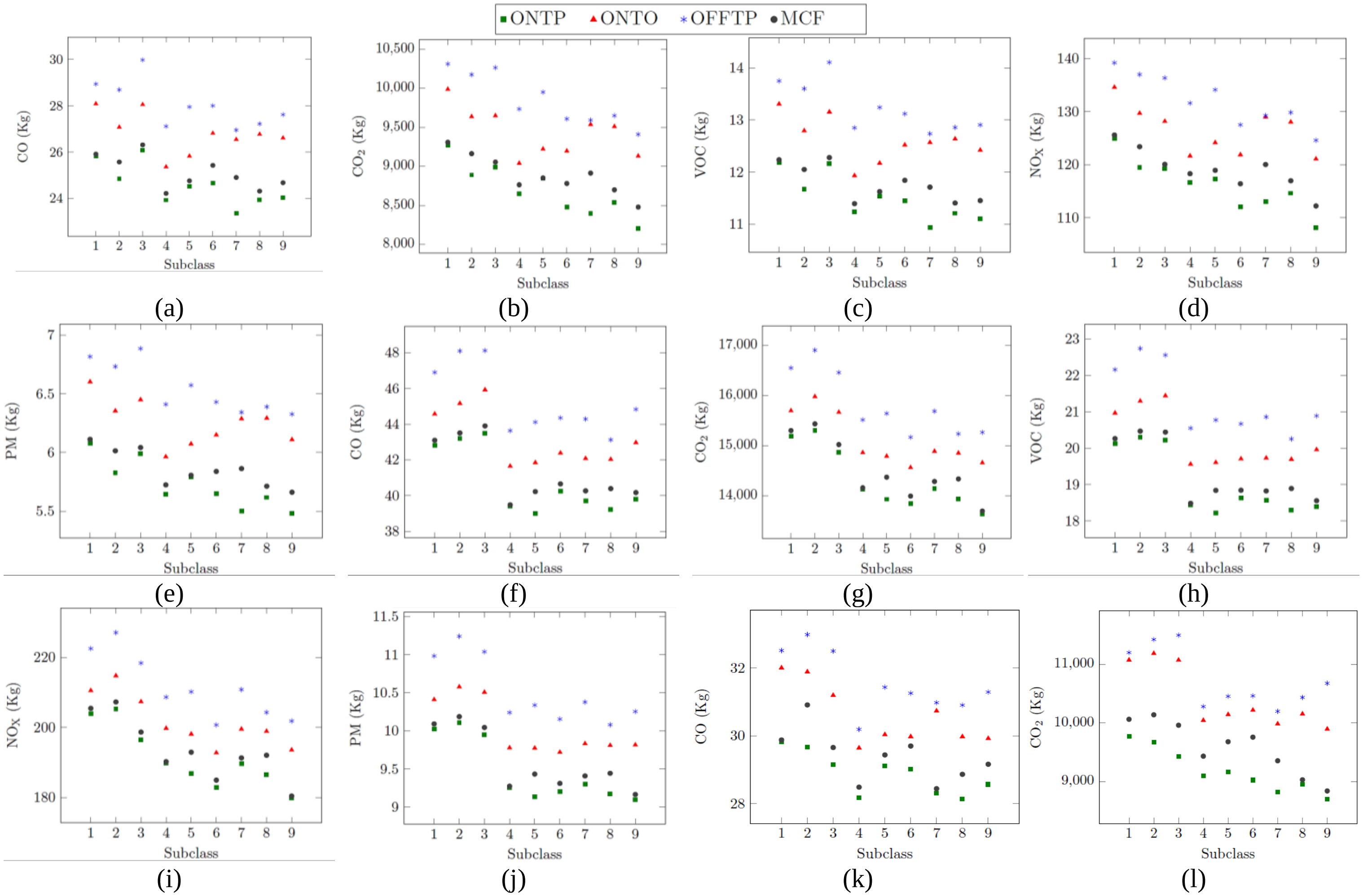


Figure 4.11 Total mass of air emissions by subclasses according to level of ECL/level of PS: (a) – (e) ONEC/60; (f) – (j) ONEC/100; (k) – (o) OFFEC/60; (p) – (t) OFFEC/100

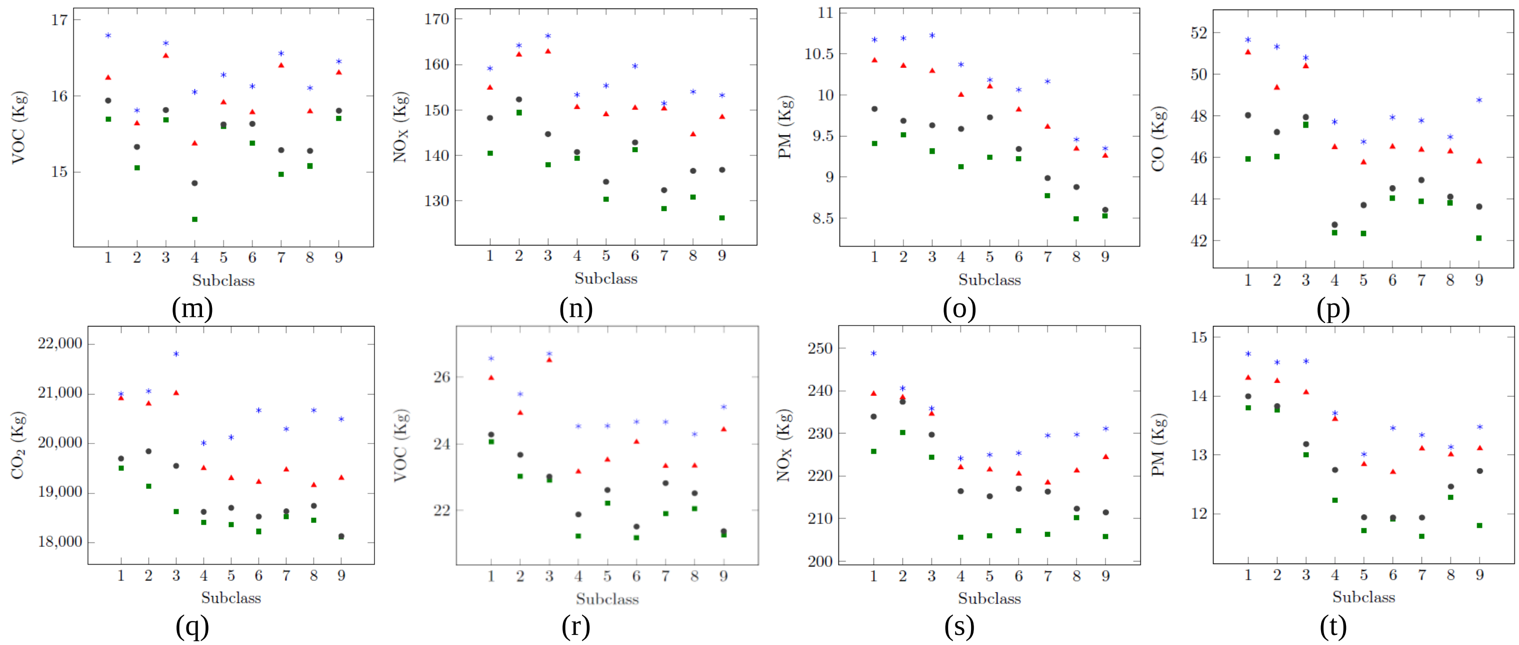


Figure 4.11 (continued) Total mass of air emissions by subclasses according to level of ECL/level of PS: (a) – (e) ONEC/60; (f) – (j) ONEC/100; (k) – (o) OFFEC/60; (p) – (t) OFFEC/100

4.5.9 Discussion

As mentioned, the future of the U.S. chassis supply model will be dependent on the interplay of various stakeholders' interests. According to the experimental results, the best chassis supply model from different stakeholders' point of views can be summarized as follows.

- Trucking company: the optimal models are COOP, T and RONT models. This is because these models would yield the lowest drayage operation time and percentage of empty movements which maximize the efficiency and profitability of drayage operation for a trucking company.
- Shipper/Receiver: the optimal models are COOP, RONT, and T models. This is because these models would yield the lowest drayage operation time and percentage of empty movements which improve drayage efficiency and keep the drayage costs low.
- Terminal operator: the optimal models are ROFFT and MC. This is because these models would move the chassis yard to a location outside the terminal and therefore maximize the land use productivity inside the terminal. Also, they eliminate delays in locating and attaching a serviceable chassis at the terminal which improves terminal productivity.
- Public agencies: the optimal models are COOP, RONT, and T models. This is because these models would yield the lowest drayage operation time, percentage of empty movements and air emissions. The lower drayage operation time and percentage of empty movements will lead to lower volume of trucks on roads around the terminal, which will reduce congestion and noise in these areas. In

addition, these models will put the chassis yard inside the terminal, and hence, reduce conflicts with zoning and land-use development around the terminals.

4.6 CONCLUSION

This paper developed a model to study the effectiveness of different U.S. chassis supply models. It extends previous drayage models by incorporating these features: (1) treating tractor, container, and chassis as separate resources which are provided in different locations, (2) ensuring that container and chassis are of the same size and type, and (3) considering the possibility that drayage companies can subcontract the work to independent owner-operators whose trucks will originate from and terminate at different locations. The resulting model is a mixed-integer quadratic programming model that solves the scheduling of tractor, loaded container, empty container and chassis in drayage operation in an integrated manner. The mathematical model is an extension of the multiple traveling salesman problem with time windows (m-TSPTW). A reactive tabu search algorithm (RTS) combined with an insertion heuristic was developed to solve the integrated optimization model. To demonstrate the feasibility of the developed model and solution methodology, they are tested on a hypothetical network via a series of experiments with real life characteristics. The RTS solutions demonstrated that the developed integrated model is capable of finding the optimal solutions and is solvable within reasonable time for an operational problem. The developed integrated model allowed for assessing the effectiveness of different U.S. chassis supply models from different chassis stakeholders' perspective. Experimental results indicated that the co-op pool, terminal pool and rental pool with chassis yard located inside the terminal yield the lowest drayage operation time, percentage of empty movement, and air emissions. This study has a few limitations that should be taken into account: (1) the drayage problem was treated as a static and deterministic problem, and hence, it did not account for traffic congestion, terminal congestion, and other unexpected delays that often arise in real world situations, (2) demands were assumed to be known a priori, but in practice there are situations when jobs are cancelled and new ones are added on the fly, (3) it is assumed that trucks stay at customer locations during packing and unpacking process, but this is not always the case, and (4) the reported results are based on a hypothetical network and they cannot be generalized beyond the network configuration and characteristics considered.

ACKNOWLEDGMENT

This paper is based upon work supported by the National Science Foundation under Grant no. 1100227.

CHAPTER 5: IMPACT OF SECOND-TIER CONTAINER PORT FACILITIES ON DRAYAGE OPERATION [4]

[4] Shiri, S., Smith, D., N, Huynh, N., Harder, F., Impact of second-tier container port facilities on drayage operation. Submitted in Transport. Res. Part E.

ABSTRACT

An increasing number of container and chassis staging, “dray-off”, drop yard, and depot facilities are being established outside of North American marine container terminals. The increased use of these “second-tier” facilities implies that there must be some capacity, delivery time, service, or reliability benefit that offsets the additional cost and complexity. This paper contributes to the field by extending a previously developed drayage scheduling model to capture the impact of second-tier port facilities on drayage operation. The experimental results indicate that second-tier facilities can yield overall efficiency and service benefits within a complex container port system.

5.1 INTRODUCTION

There is an observable trend in the North American container port industry toward the establishment of auxiliary or satellite facilities to store, stage, or transfer loaded containers, empty containers, and bare container chassis outside port container terminals. On the surface, these “second-tier” facilities would appear to duplicate the functions of the marine container terminals themselves, and to add steps to the import or export handling process. This trend may seem counter-intuitive in an industry obsessed with efficiency. The increased use of second-tier facilities implies that there must be some capacity, delivery time, service, or reliability benefit that offsets the additional cost and complexity. This paper seeks to determine the impact of second-tier facilities on drayage operation.

The drayage scheduling problem is a variation of the pickup-and-delivery problem (PDP) in which vehicle capacity equals one, since it involves picking up a container from one place and delivering it to another. A comprehensive review of PDP can be found in

Savelsbergh and Sol (1995), Berbeglia et al. (2007), Mahmoudi and Zhou (2016) and Mahmoudi et al. (2016). Several studies have formulated the drayage problem as a PDP. These studies include the work of Wang and Regan (2002), Ileri et al. (2006), Imai et al. (2007), Caris and Janssen (2009), and Nossack and Pesch (2013). Since drayage operation involves the movement of the tractor, loaded container, empty container, and chassis, some studies have focused on developing drayage scheduling models that consider the movement of loaded and empty containers jointly. These studies include the work of Zhang et al. (2009, 2010, 2011), Braekers et al. (2013 and 2014), and Shiri and Huynh (2017). In recent years, a number of studies have addressed the drayage problem considering different container size. These studies include the work of Vidović et al. (2012 and 2016), Popović et al. (2014), Zhang et al. (2015), and Funke and Kopfer (2016). Drayage studies that considered time-window constraints at marine container terminals (via a truck appointment system) include the work by Namboothiri and Erera (2008), and Shiri and Huynh (2016). Cheung and Hange (2003), Cheung et al. (2005 and Shiri et al. (2018) have addressed the dynamic or stochastic version of the drayage problem. A few studies have considered the collaboration between drayage companies. These studies include the work of Sterzik et al. (2015) and Wang and Kopfer (2015). A complete review of drayage studies can be found in the works of Shiri and Huynh (2017 and 2016), Wang and Kopfer (2015), and Braekers et al. (2013). To date, no study has examined the impact of drop yards and other second-tier facilities as a whole on drayage operation.

To determine the impact of second-tier facilities on drayage operation this study builds on our previously developed drayage scheduling model (2017). This model is a mixed-integer quadratic programming model that solves the scheduling of tractor, loaded container, empty container, and chassis in an integrated manner. For this study, the following modifications are made to the model: (1) trucks do not have to wait at customers' locations during the im7port unloading and export loading operations; (2) drayage operations can include a drop yard (i.e., second-tier facility) for picking up or/and dropping off loaded containers outside the marine container terminal; and (3) the job requests by customers are extended to include empty container pickup, loaded container pickup, empty container delivery, and loaded container delivery. To solve this model, a reactive tabu search algorithm (RTS) combined with an insertion heuristic developed by the authors is used. The impact of second-tier facilities on drayage operation time is assessed via a set of experiments that consider 12 different situations involving different locations for import pickup, export delivery, chassis yard, and empty container depot.

5.2 BACKGROUND

5.2.1 Evolving Container Terminal Functions

Specialized marine container terminals have evolved from multi-purpose general cargo terminals. At such terminals, cargo was handled piecemeal in crates, on pallets, in bundles, or however it was packaged. With containerization, many terminals had an on-site container freight station (CFS) to consolidate or deconsolidate piecemeal shipments before or after movement in containers aboard vessels. Both loaded and empty containers were commonly kept on chassis ("wheeled") in the terminal, and both container and chassis equipment were maintained at the terminal as well. Marine container terminals were thus self-contained. Full container load importers sent truck tractors to pick up loaded import containers on chassis and returned the empty containers on chassis to the same terminal.

Less-than-container-load shippers picked up their imports or delivered their exports at the on-terminal CFS.

As containerization progressed and volumes grew, container terminals first grew outward then upward. Wheeled storage is the least costly marine terminal operating method when land is available. Terminal operators, therefore, preferred to expand outward and keep storing containers on chassis where possible. Where land was not readily or economically available, terminal operators began to stack containers and park the chassis separately. Groups of containers were generally stacked in this order as required:

- **Empty containers**. Empty containers are stacked by owner, type, and size. Empties can be handled last-in, first-out (LIFO) since the operator need only locate the first container meeting the customer's order.
- **Export loads.** Export loads are stacked by size, weight, and vessel/voyage as they are received from the customer. Export loads are retrieved from the stacks during vessel operations.
- **Import loads.** Import loads are "high-piled" as they are unloaded from the vessel. Since a specific container must be retrieved, the yard crane operator must frequently "dig" through the stack. This process is known to increase cost and delay.
- **Refrigerated and special loads.** Refrigerated, oversized, and other loads (e.g. tank-type containers) requiring special handling are typically kept on chassis.

Marine terminal operators also freed up valuable space by moving some functions off the terminal, beginning with container freight stations. Changes to labor agreements and industry practices led to the closure of on-terminal CFSs and establishment of independent, off-terminal consolidators. Consolidators often added other functions and evolved into multi-purpose third-party logistics firm (3PLs).

Container repair and storage of off-hire leasing company containers was progressively moved to independent off-terminal depots. Although sometimes draymen would obtain or return a container at the depot, for some time the usual practice was to complete all such transactions at the marine terminal. Empties were shuttled between terminal and depot as needed.

Prior to the 2008 recession, East Coast and Gulf Coast container terminals with limited space typically stacked their containers. High-priority import loads and specialized loads may have been kept on chassis where possible. West Coast terminals that had more space had mixed operations, with empties and perhaps some export loads stacked, but import loads usually kept on wheels (i.e., chassis). Some West Coast terminals that were mostly stacked before the recession reverted to less costly wheeled operations when volumes dropped.

Two post-recession trends have led to near-universal stacking operations in major U.S. container terminals:

- Dramatic post-recession trade recovery, which required higher storage densities in existing terminal footprints.
- Progressive ocean carrier withdrawal from chassis supply, requiring separate storage of ocean-carrier containers and third-party chassis.

The first trend affected all terminals, while the second led most West Coast terminals to abandon wheeled storage except for special container types.

To continue increasing throughput on the same footprint, terminal operators had to either stack higher (with associated capital and operating cost penalties) or shift additional functions off the terminal. Terminals often pursued a combined strategy, investing in lift equipment to stack loaded containers higher, and shifting more chassis and empty storage to off-site locations.

Chassis were shifted off-site not only to free up terminal space but because the chassis was now often owned by third-party pools rather than by the terminals or their ocean carrier tenants. Previously, on-terminal storage of carrier-owned chassis was part of the business relationship between the carrier and terminal. Now, terminals seek to right-size chassis fleets: maintaining enough for immediate needs and moving the rest to an off-site location. Some terminals have proposed storage charges on excess chassis inventory.

The growing complexity of alliances and carrier/terminal arrangements also meant that an empty container often had to be delivered to a terminal that would not accept the chassis on which it was mounted. Chassis pool operators set up off-terminal yards to accommodate both storages of excess inventory and the need for these “split returns.”

These converging developments have led container depot operators and chassis pool operators to establish a web of depots and pool yards around major container ports. At the Port of Vancouver, B.C., for example, around 75% of all empty containers are held in off-terminal depots. Besides container depot operators, British Columbia drayage firms and export transloaders have entered the container storage business.

5.2.2 Second-Tier Facilities

A new type of second-tier facility has recently emerged alongside container depots and chassis pools. These facilities are essentially holding or staging areas for containers or trucks. Examples include off-terminal staging yards (drop yards) for import loads on chassis, such as those operated by Shippers Transport Express at Los Angeles/Long Beach, Oakland, and French Camp, CA, or the facility operated by TTSI at Los Angeles (Figure 5.1).

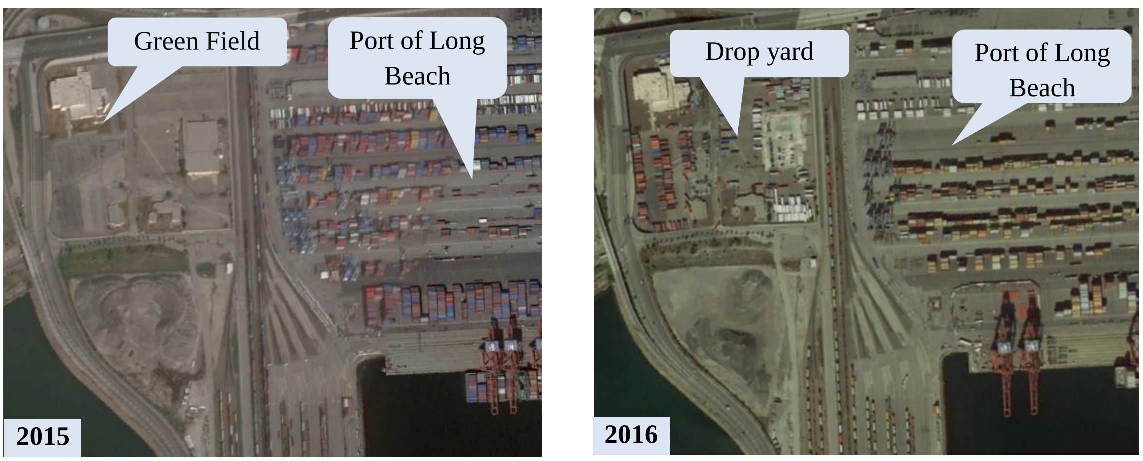


Figure 5.1 Newly Stablished Drop Yard at the Port of Long Beach

The truck staging yards at the Ports of Virginia and Tacoma effectively extend the capacity of inbound terminal gate queues in a controlled fashion rather than simply allowing queues to expand indefinitely. The loaded container staging yards at the California ports serve a different purpose: increasing terminal fluidity and capacity and improving customer service.

The Shipper Transport Express (STE) staging yards in Southern California and Oakland hold import containers on chassis ready for pickup. These facilities usually have shorter queues, shorter turn times, and longer gate hours than the marine terminals themselves. STE trucks and drivers shuttle the containers on chassis from the SSA terminals.

The TTSI yard in Southern California has a similar function but a different operating approach. Import containers on chassis are pulled from marine container terminals at the importer's request and held for pickup at the TTSI site. These two-stage drayage operations are known as "dray offs." Ironically, this practice was forbidden in the early days of the Southern California clean truck programs. At that time, some operators used a few low-emission "clean" trucks to shuttle containers between marine terminals and nearby lots, with actual delivery made by older, "dirtier" trucks.

Increased use of off-terminal staging has been prompted by the Southern California PierPASS/OffPeak program. This program, initiated in 2005, charges a Traffic Mitigation Fee (TMF) for daytime loaded container moves at Long Beach and Los Angeles. The TMF revenue is used to support night gate operations, when there is no fee. Importers prefer to avoid the TMF whenever possible, but must still receive much of the import flow during the day. Accordingly, it is common for Southern California drayage firms to pull import containers from the marine terminals during the night and hold them at formal or informal staging facilities for subsequent daytime delivery. The process can be reversed for export containers, shipping from the export location during the day but delivering to the marine terminal at night.

The current dray-off operations, whether conducted at the terminal's initiative or the customer's initiative, have multiple potential benefits:

- Acting as additional terminal storage, relieving pressure on the actual marine terminal and increasing terminal throughput capacity by reducing on-terminal dwell time.
- Acting as buffers for import drayage operators and their customers. Containers can be shuttled to the off-terminal staging yard at night when terminal lines are shorter (and when there is day shift TMF in Southern California). The customers' draymen can then pick up the containers during the day shift without having to visit the marine terminals.
- Helping importers avoid storage charges by pulling import containers from the marine terminals before their free time limit is reached.

These off-terminal staging yards may also take advantage of terminal "peel off" or "free flow" options. In "peel off" or "free flow" operations (known as "speed gates" at Vancouver, BC), import customers or drayage firms designate a series of containers (usually 25–50) from a particular vessel to be stacked and retrieved last-in-first-out (LIFO). Each drayman for that customer receives the next container off the stack rather than waiting to have a specific container located and pulled. These peel-off operations save time for both marine terminal operators and drayage firms. A dray-off yard operator such as STE or TTSI that can arrange to pick up containers from a peel-off stack during extended gate hours will achieve substantially higher productivity.

The emergence of these different second-tier facilities means that a growing proportion of transactions that formerly occurred at marine container terminals are taking place elsewhere.

- In Southern California, one set of drayage drivers may work between the staging yards and the inland customers while a second set works to and from the marine terminal.
- At Oakland, a drayage firm can sometimes return an empty and pick up an import load at satellite facilities without ever entering a marine terminal.
- At Vancouver, BC., most empty container pickups and returns take place at off-terminal facilities.

While these off-terminal transactions may be advantageous for over-the-road draymen they come at a cost:

- Separate shuttle drayage trips link the staging yard with the terminal, and those trips must still pass through the terminal gates and be handled in the terminal container yard.
- The off-site facilities have land, capital, and operating costs that duplicate some of the marine terminal functions.
- The use of off-terminal chassis pools and container depots adds legs to drayage truck trips. A former in-and-out trip may become a triangular trip with the need to drop or obtain equipment at a non-terminal location.

The growth and success of these second-tier port facilities imply that they confer net benefits. Just how and under what circumstances those net benefits are achieved is the research question for this paper.

5.3 PROBLEM DESCRIPTION AND FORMULATION

5.3.1 Notation

The notations used to describe the drayage scheduling problem are as follows.

N_{LP}	Set of loaded container pickup nodes
N_{EP}	Set of empty container pickup nodes
N_{LD}	Set of loaded container delivery nodes
N_{ED}	Set of empty container delivery nodes
N_J	Set of job nodes, $N_J = N_{LP} \cup N_{EP} \cup N_{LD} \cup N_{ED}$
N_D	Set of drayage company's truck depot nodes
$N_{D'}$	Set of owner-operator facility nodes
T^i	Set of trucks initially located at truck depot/owner-operator facility node i
T	Set of all trucks, $T = \bigcup_{i \in N_D \cup N_{D'}} T^i$
T^{DC}	Set of drayage company's trucks, $T^{DC} = \bigcup_{i \in N_D} T^i$
n_i	Number of trucks initially located at truck depot/owner-operator facility node i
$[L_i, U_i]$	Time window of job node i at the customer location
ST_i	Service time of node i
TT_{ij}	Transfer time on arc (i, j)
W^k	A constant, 1 for drayage company's trucks and 50 for owner-operators' trucks
M	A sufficiently large constant

ST_i	Service time of node i
TT_{ij}	Transfer time on arc (i, j)
PEC	Time to pick up an empty container
DEC	Time to drop off an empty container
PLC	Time to pick up a loaded container
DLC	Time to drop off a loaded container
PCH	Time to pick up the chassis
DCH	Time to drop off chassis
SCH	Time to swap chassis
T(i,j)	Travel time between locations i and j
GT_i	Gate queuing time at location i
T	Marine terminal
TD_i	Truck depot/owner-operator facility location i
CL_i	Customer location i
CHY	Chassis yard
ECD	Empty container depot
DY	Drop yard

5.3.2 Drayage Problem and Assumptions

Figure 5.2a shows the traditional movement of import and export containers in and out of the terminal. In this scenario, trucks travel to the marine terminal to pick up loaded import containers and drop off loaded export containers. With the emergence of second-tier facilities, import containers are stored at an off-terminal location called a drop yard (Figure 5.2b). In this scenario, trucks visit the drop yard to pick up import containers; however, they still need to go to the marine terminal to deliver export containers. In another scenario with drop yards, both import and export containers are stored in the drop yard on chassis (Figure 5.2c). In this scenario, trucks perform import pickups and export drop-offs at the drop yard.

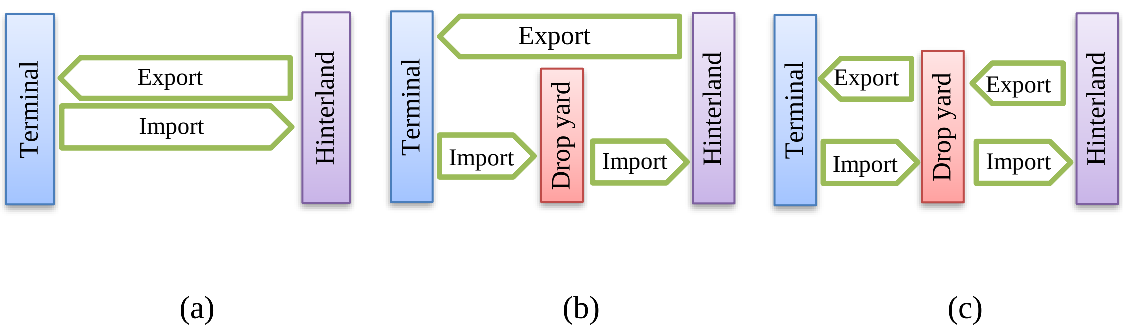


Figure 5.2 Drayage practice: (a) traditional drayage process; (b) drayage with drop yard used for imports; (c) drayage with drop yard used for both exports and imports

To evaluate the impact of drop yards, three scenarios are considered as follows.

Scenario 1: Import pickup and export delivery locations are inside the marine terminal (Figure 5.2a)

Scenario 2: Import pickup location is at an off-terminal drop yard and export delivery location is inside the marine terminal (Figure 5.2b)

Scenario 3: Import pickup and export delivery locations are at an off-terminal drop yard (Figure 5.2c)

In this study, it is assumed that trucks are not required to stay at the customers' locations during the import unloading and export loading operations. The practice of dropping off a loaded import container and retrieving an empty container from the customer is often called "drop and pick", as opposed to "stay with" operations in which the driver waits for cargo to be unloaded or loaded. Drop and pick operations are the dominant form of drayage in many large ports. As a result, four types of jobs are assumed:

- Empty container pickup at customer location
- Loaded container pickup at customer location
- Empty container delivery at customer location
- Loaded container delivery at customer location

A customer is allowed to request any of the aforementioned four jobs. The drayage company is considered to have a limited number of trucks and multiple truck depots or driver domiciles (often the driver's home). These trucks must start at one of the company's depots or domiciles and should return to nearest company depot. In addition, the drayage company can subcontract the work to independent owner-operators whose trucks will originate from and terminate at an owner-operator facility (again, typically the driver's home). Two different chassis yard locations are considered: (1) inside the marine terminal, and (2) outside the marine terminal. In addition, two different scenarios for the storage of empty containers are considered: (1) inside the marine terminal, and (2) outside the marine terminal. Finally, it is assumed that all jobs are known *a priori*, and all travel times are deterministic, and thus, the drayage problem studied in this paper is classified as static and deterministic.

5.3.3 Graphical Representation of the Drayage Problem

The authors (Shiri and Huynh, 2017) previously developed an integrated drayage scheduling model which considers the tractor, chassis, and container as separate resources. The formulation is based on a graph representation of the various drayage activities. This study builds on our prior work. The following provides a summary of our formulation and a description of the modifications made for this study.

Let $G(N, A)$ be a graph that depicts the various drayage activities, where N is the set of nodes and A is the set of arcs. The N nodes consist of either a depot node or a job node. A depot node consists of drayage company's truck depot nodes and owner-operator facility nodes which specifies the number of trucks initially located at the truck depots and at the owner-operators' facilities, respectively. A job node is defined as a series of activities that should be performed at the customer location for each type of job. The types of job nodes are modified in this study. Instead of having just import and export job nodes, the following job nodes are considered: loaded container pickup nodes (N_{LP}), empty container pickup nodes (N_{EP}), loaded container delivery nodes (N_{LD}), and empty container delivery nodes (N_{ED}). The time it takes to complete all of these activities is called the service time (ST_i). The activities and times associated with each job are as follows.

- For N_{EP}: time to pick up an empty container from the customer
- For N_{LP}: time to pick up a loaded container from the customer
- For N_{ED}: time to drop off an empty container to the customer
- For N_{LD}: time to drop off a loaded container to the customer

Another attribute of the job nodes is the time window, denoted by [L_i, U_i]. The time window of a job node indicates the time interval within which activities at this node (at customer location) should start.

Table 5.1 Transfer Time of Arc (*i*, *j*) for Scenario 1

TT_{ij}		To node j			
		N_D / $N_{D'}$	N_{EP}/N_{LP}	N_{ED}	N_{LD}
From node i	N_D/ $N_{D'}$	-	$T(TD_i,CHY) + GT_{CHY} + PCH + T(CHY,CL_j) + GT_{CL}$	$T(TD_i,CHY) + GT_{CHY} + PCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD,CL_j) + GT_{CL}$	$T(TD_i,CHY) + GT_{CHY} + PCH + T(CHY,T) + GT_T + PLC + T(T,CL_j) + GT_{CL}$
	N_{EP}	$T(CL_i,ECD) + GT_{ECD} + DEC + (ECD,CHY) + GT_{CHY} + DCH + T(CHY,TD_j)$	IF S(i)= S(j)[1] $T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CL_j) + GT_{CL}$ ELSE $T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + SCH + T(CHY, CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,CL_j) + GT_{CL}$ ELSE $T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + SCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,T) + GT_T + PLC + T(T, CL_j) + GT_{CL}$ ELSE $T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + SCH + T(CHY,T) + GT_T + PLC + T(T, CL_j) + GT_{CL}$
	N_{LP}	$T(CL_i,T) + GT_T + DLC + T(T,CHY) + GT_{CHY} + DCH + T(CHY,TD_j)$	IF S(i)= S(j) $T(CL_i,T) + GT_T + DLC + T(T,CL_j)$ ELSE $T(CL_i,T) + GT_T + DLC + T(T,CHY) + GT_{CHY} + SCH + T(CHY,CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,T) + GT_T + DLC + T(T,ECD) + PEC + T(ECD,CL_j) + GT_{CL}$ ELSE $T(CL_i,T) + GT_T + DLC + T(T,CHY) + GT_{CHY} + SCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,T) + GT_T + DLC + PLC + T(T,CL_j) + GT_{CL}$ ELSE $T(CL_i,T) + GT_T + DLC + T(T,CHY) + GT_{CHY} + SCH + T(CHY,T) + GT_T + PLC + T(T,CL_j) + GT_{CL}$
	N_{ED}/ N_{LD}	$T(CL_i,CHY) + GT_{CHY} + DCH + T(CHY,TD_j)$	IF S(i)= S(j) $T(CL_i,CL_j) + GT_{CL}$ ELSE $T(CL_i,CHY) + GT_{CHY} + SCH + T(CHY,CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}$ ELSE $T(CL_i,CHY) + GT_{CHY} + SCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,T) + GT_T + PLC + T(T, CL_j) + GT_{CL}$ ELSE $T(CL_i,CHY) + GT_{CHY} + SCH + T(CHY,T) + GT_T + PLC + T(T,CL_j) + GT_{CL}$

[1] If chassis and/or containers can be used for job *j* after job *i*

The arc (*i*, *j*) represents the transfer time between two nodes. Transfer time on the arc (*i*, *j*) includes:

1. Activities that performed between the customer location and terminal/drop yard/chassis yard/empty container depot, and at the terminal/drop yard/chassis yard/empty container depot
2. Activities between node *i* activities and before the commencement of node *j*

Table 5.2 Transfer Time of Arc (*i*, *j*) for Scenario 2

TT_{ij}		To node j			
		N_D / $N_{D'}$	N_{EP}/N_{LP}	N_{ED}	N_{LD}
From node i	N_D/ $N_{D'}$	-	$T(TD_i,CHY) + GT_{CHY} +$ $PCH + T(CHY,CL_j) + GT_{CL}$	$T(TD_i,CHY) + GT_{CHY} + PCH +$ $T(CHY,ECD) + GT_{ECD} + PEC +$ $T(ECD,CL_j) + GT_{CL}$	$T(TD_i,DY) + GT_{DY}$ $+ PLC + T(DY,CL_j)$ $+ GT_{CL}$
From node i	N_{EP}	$T(CL_i,ECD)$ $+ GT_{ECD} +$ $DEC +$ (ECD,CHY) $+ GT_{CHY} +$ $DCH +$ $T(CHY,TD_j)$	IF S(i)= S(j)[1] $T(CL_i,ECD) + GT_{ECD} +$ $DEC + T(ECD,CL_j) + GT_{CL}$ ELSE $T(CL_i,ECD) + GT_{ECD} +$ $DEC + T(ECD,CHY) +$ $GT_{CHY} + SCH + T(CHY,$ $CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,CL_j) + GT_{CL}$ ELSE $T(CL_i,ECD) + GT_{ECD} + DEC +$ $T(ECD,CHY) + GT_{CHY} + SCH +$ $T(CHY,ECD) + GT_{ECD} + PEC +$ $T(ECD, CL_j) + GT_{CL}$	$T(CL_i,ECD) +$ $GT_{ECD} + DEC +$ $T(ECD,CHY) +$ $GT_{CHY} + DCH +$ $T(CHY,DY) + GT_{DY}$ $+ PLC + T(DY,CL_j)$ $+ GT_{CL}$
From node i	N_{LP}	$T(CL_i,T) +$ $GT_T + DLC$ $+ T(T,CHY)$ $+ GT_{CHY} +$ $DCH +$ $T(CHY,TD_j)$	IF S(i)= S(j) $T(CL_i,T) + GT_T + DLC +$ $T(T,CL_j) + GT_{CL}$ ELSE $T(CL_i,T) + GT_T + DLC +$ $T(T,CHY) + GT_{CHY} + SCH$ $+ T(CHY,CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,T) + GT_T + DLC + T(T,ECD)$ $+ GT_{ECD} + PEC + T(ECD,CL_j) +$ GT_{CL} ELSE $T(CL_i,T) + GT_T + DLC +$ $T(T,CHY) + GT_{CHY} + SCH +$ $T(CHY,ECD) + GT_{ECD} + PEC +$ $T(ECD, CL_j) + GT_{CL}$	$T(CL_i,T) + GT_T +$ $DLC + T(T,CHY) +$ $GT_{CHY} + DCH +$ $T(CHY,DY) + GT_{DY}$ $+ PLC + T(DY,CL_j)$ $+ GT_{CL}$
From node i	N_{ED}/ N_{LD}	$T(CL_i,CHY)$ $+ GT_{CHY}$ $+ DCH +$ $T(CHY,TD_j)$	IF S(i)= S(j) $T(CL_i,CL_j) + GT_{CL}$ ELSE $T(CL_i,CHY) + GT_{CHY} +$ $SCH + T(CHY,CL_j) + GT_{CL}$	IF S(i)= S(j) $T(CL_i,ECD) + GT_{ECD} + PEC +$ $T(ECD, CL_j) + GT_{CL}$ ELSE $T(CL_i,CHY) + GT_{CHY} + SCH +$ $T(CHY,ECD) + GT_{ECD} + PEC +$ $T(ECD, CL_j) + GT_{CL}$	$T(CL_i,CHY) +$ $GT_{CHY} + DCH +$ $T(CHY,DY) + GT_{DY}$ $+ PLC + T(DY,CL_j)$ $+ GT_{CL}$

[1] If chassis and/or containers can be used for job *j* after job *i*

The transfer time on the arc (*i*, *j*) depends on the combination of nodes that occur at *i* and *j*, as well as the position of import pickup location, export delivery location, chassis yard, and empty container depot. The transfer time for all possible combinations of nodes and scenarios is provided in Tables 5.1 to 5.3. It should be noted that chassis and/or containers can be used for job *j* after job *i* if the container in jobs *i* and *j* have the same size and type. For example, 20-ft refrigerated containers require 20-ft chassis that are equipped with a generator to provide electric power to the containers. It should also be noted that if the chassis yard and empty container depot are located inside the marine terminal, then there is only one gate queuing time. If they are located outside the marine terminal, then there is a separate gate queuing time at each of the three facilities (chassis yard, empty container depot, and marine terminal).

Table 5.3 Transfer Time of Arc (*i*, *j*) for Scenario 3

TT_{ij}		To node j			
		N_D /$N_{D'}$	N_{EP}/N_{LP}	N_{ED}	N_{LD}
From node i	N_D / $N_{D'}$	-	T(TD_i,CHY) + GT_{CHY} + PCH + T(CHY,CL_j) + GT_{CL}	T(TD_i,CHY) + GT_{CHY} + PCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD,CL_j) + GT_{CL}	T(TD_i,DY) + GT_{DY} + PLC + T(DY,CL_j) + GT_{CL}
	N_{EP}	T(CL_i,ECD) + GT_{ECD} + DEC + (ECD,CHY) + GT_{CHY} + DCH + T(CHY,TD_j)	IF S(i)= S(j)[1] T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CL_j) + GT_{CL} ELSE T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + SCH + T(CHY, CL_j) + GT_{CL}	IF S(i)= S(j) T(CL_i,CL_j) + GT_{CL} ELSE T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + SCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}	T(CL_i,ECD) + GT_{ECD} + DEC + T(ECD,CHY) + GT_{CHY} + DCH + T(CHY,DY) + GT_{DY} + PLC + T(DY,CL_j) + GT_{CL}
	N_{LP}	T(CL_i,DY) + GT_{DY} + DLC + T(DY,TD_j)	T(CL_i,DY) + GT_{DY} + DLC + T(DY,CHY) + GT_{CHY} + PCH + T(CHY,CL_j) + GT_{CL}	T(CL_i,DY) + GT_{DY} + DLC + T(DY,CHY) + GT_{CHY} + PCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD,CL_j) + GT_{CL}	T(CL_i,DY) + GT_{DY} + DLC + PLC + T(DY,CL_j) + GT_{CL}
	N_{ED}/ N_{LD}	T(CL_i,CHY) + GT_{CHY} + DCH + T(CHY,TD_j)	IF S(i)= S(j) T(CL_i,CL_j) + GT_{CL} ELSE T(CL_i,CHY) + GT_{CHY} + SCH + T(CHY,CL_j) + GT_{CL}	IF S(i)= S(j) T(CL_i,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL} ELSE T(CL_i,CHY) + GT_{CHY} + SCH + T(CHY,ECD) + GT_{ECD} + PEC + T(ECD, CL_j) + GT_{CL}	T(CL_i,CHY) + GT_{CHY} + DCH + T(CHY,DY) + GT_{DY} + PLC + T(DY,CL_j) + GT_{CL}

[1] If chassis and/or containers can be used for job *j* after job *i*

5.3.4 Mathematical Formulation

Decision variables, objective function, and constraints of the mathematical formulation are presented below (Shiri and Huynh, 2017).

$$x_{ij}^{k} = \begin{cases} 1 & \text{If job node } i \text{ and job node } j \text{ are served consecutively by truck } k \\ 0 & \text{Otherwise} \end{cases}$$

s_i = Time that the first activity on node i is started

$$\begin{aligned} \text{Minimize } & \sum_{k\in T^{DC}} \sum_{i\in N_D} \sum_{j\in N_J} s_j \times W^k \times x_{ji}^k + \sum_{k\in T^i} \sum_{i\in N_{D'}} \sum_{j\in N_J} s_j \times W^k \times x_{ji}^k - \\ & \sum_{k\in T^i} \sum_{i\in N_D \cup N_{D'}} \sum_{j\in N_J} s_j \times W^k \times x_{ij}^k + \sum_{k\in T^i} \sum_{i\in N_D \cup N_{D'}} \sum_{j\in N_J} TT_{ij} \times W^k \times x_{ij}^k + \\ & \sum_{k\in T^{DC}} \sum_{i\in N_D} \sum_{j\in N_J} (ST_j + TT_{ji}) \times W^k \times x_{ji}^k + \sum_{k\in T^i} \sum_{i\in N_{D'}} \sum_{j\in N_J} (ST_j + TT_{ji}) \times W^k \times x_{ji}^k \end{aligned} \tag{5.1}$$

$$\sum_{j\in N_J} \sum_{k\in T^i} x_{ij}^k \le n_i \qquad \forall i \in N_D \cup N_{D'} \tag{5.2}$$

$$\sum_{j\in N_J} x_{ij}^k \le 1 \qquad \forall i \in N_D \cup N_{D'}, \forall k \in T^i \tag{5.3}$$

$$\sum_{j\in N_J} x_{ij}^k = \sum_{d\in N_D} \sum_{j\in N_J} x_{jd}^k \qquad \forall i \in N_D, \forall k \in T^i \tag{5.4}$$

$$\sum_{j\in N_J} x_{ij}^k = \sum_{j\in N_J} x_{ji}^k \qquad \forall i \in N_{D'}, \forall k \in T^i \tag{5.5}$$

$$\sum_{k\in T} \sum_{j\in N_J} x_{ji}^k + \sum_{k\in T^j} \sum_{j\in N_D \cup N_{D'}} x_{ji}^k = 1 \qquad \forall i \in N_J \tag{5.6}$$

$$\sum_{k\in T} \sum_{j\in N_J} x_{ij}^k + \sum_{k\in T^{DC}} \sum_{j\in N_D} x_{ij}^k + \sum_{k\in T^j} \sum_{j\in N_{D'}} x_{ij}^k = 1 \qquad \forall i \in N_J \tag{5.7}$$

$$x_{di}^k + \sum_{j\in N_J} x_{ji}^k = \sum_{j\in N_J} x_{ij}^k + \sum_{j\in N_D} x_{ij}^k \qquad \forall i \in N_J, \forall d \in N_D, \forall k \in T^d \tag{5.8}$$

$$x_{di}^k + \sum_{j\in N_J} x_{ji}^k = \sum_{j\in N_J} x_{ij}^k + x_{id}^k \qquad \forall i \in N_J, \forall d \in N_{D'}, \forall k \in T^d \tag{5.9}$$

$$TT_{ij} - (1 - x_{ij}^k) \times M \le s_j \qquad \forall i \in N_D \cup N_{D'}, \forall j \in N_J, \forall k \in T^i \qquad (5.10)$$

$$s_i + TT_{ij} + ST_i - (1 - x_{ij}^k) \times M \le s_j \qquad \forall i, j \in N_J, \forall k \in T \qquad (5.11)$$

$$L_i \le s_i \le U_i \qquad \forall i \in N_J \qquad (5.12)$$

$$x_{ij}^k \in \{0,1\} \qquad \forall i, j \in N_J \cup N_D \cup N_{D'}, \forall k \in T \qquad (5.13)$$

$$s_i \ge 0 \qquad \forall i \in N_J \qquad (5.14)$$

Equation (5.1) is the objective function which seeks to minimize the drayage operation time. W^K is weight that used to give priority to drayage company's trucks; set to 1 for drayage company's trucks and 50 for owner-operators' trucks. Constraint (5.2) is the capacity constraint for truck depots/facilities and Constraint (5.3) enforces that each truck is used at most once. Constraint (5.4) ensures that drayage company's trucks that start their route from one of the drayage company's depots will end at one of drayage company's depots. Constraint (5.5) enforces that owner-operators' trucks return to the same facility where they originated. Constraints (5.6) and (5.7) enforces that each customer is visited exactly once and by only one truck. Constraints (5.8) and (5.9) ensure that if a truck enters a job node, then it must leave it. Constraints (5.10) and (5.11) shows the time relationship among consecutive nodes along a route. Constraint (5.12) ensures that the start time of job nodes to their time windows. Constraints (5.13) and (5.14) determine the domain of the decision variables.

5.3.5 Reactive Tabu Search

The mathematical model presented in this study is NP-hard since it is an extension of the NP-hard problem m-TSPTW. Meta-heuristics such as RTS have been widely used to solve these types of problems. Our previously developed solution methodology (Shiri and Huynh, 2017) was adapted to solve realistic-sized problems in this study. The solution methodology is based on the RTS algorithm which is a memory-based metaheuristic (Battiti and Tecchiolli, 1994). It utilizes both neighborhood search and prohibition-based techniques to explore the feasible region and improve the solution. RTS consists of two phases. Phase 1 (shown in Figure 5.3) generates an initial solution via an insertion heuristic proposed by Solomon (1987). For the drayage problem, a solution is a set of routes with a set of job nodes while all constraints are satisfied. In Phase 2, the feasible region is explored via a neighborhood generation mechanism to improve the solution. The neighborhood generation mechanism in our problem consists of moving job nodes between routes or changing their positions within their current route (step 1 of Phase 2 shown in Figure 5.3). In the initial solution shown in Figure 5.3, there are two routes; route 1 consists of customers 3, 2 and 4 and route 2 consists of customers 5 and 1. In Phase 2, job node 2 was move from route 1 to the route 2.

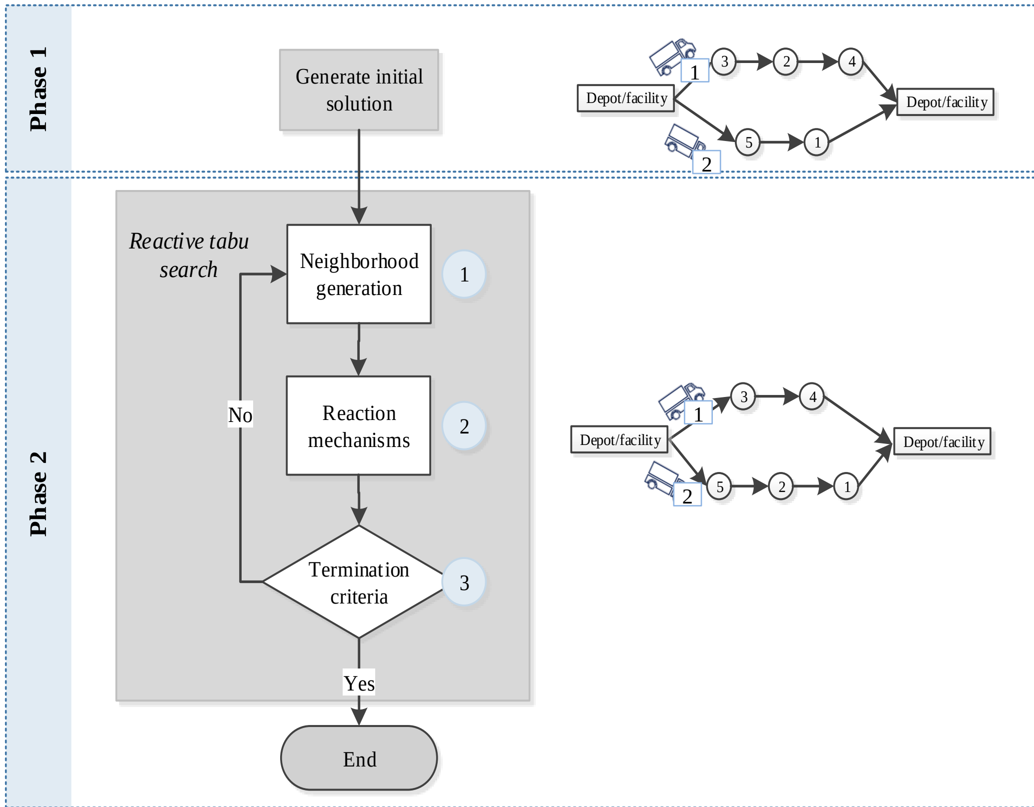


Figure 5.3 Flowchart of developed solution methodology

As mentioned, RTS also uses prohibition-based techniques, meaning that the history of visited solutions can affect the search path. RTS discourages the search from revisiting a previous solution by recording the recent history of moves as forbidden moves. These forbidden moves are kept forbidden for a period of time, known as tabu tenure. The difference between a tabu search algorithm and a reactive tabu search algorithm is that a reactive tabu search algorithm changes the tabu tenure dynamically according to the frequency of revisiting solutions (Reaction mechanisms in step 2 of Phase 2 shown in Figure 5.3). The dynamic change of tabu tenure is performed as follows. If a solution is repeated within a predefined number of iterations, then it means that the algorithm is falling into a cycle. To prevent coming back to previously-visited solutions, tabu tenure is increased. On the contrary, if a solution is not revisited in a certain number of iterations, tabu tenure is decreased to allow for exploration of new regions. Lastly, the algorithm is terminated after 25×*n* iterations where *n* is the total number of nodes (step 3 of Phase 2 shown in Figure 5.3).

5.4 NUMERICAL EXPERIMENTS

5.4.1 Experiment Design

A set of experiments was performed on randomly generated instances with real-life characteristics. Instances were generated on a 2-hour by 2-hour hypothetical network and the customer locations were generated randomly within the network perimeter. For the experiments, a network with one marine container terminal, one empty container depot, one chassis yard, one drop yard, one truck depot, and one owner-operator facility were considered. Experiments were carried out using representative transaction times for U.S. marine terminals and second-tier facilities as shown in Table 5.4.

Table 5.4 Transaction Times at T, CHY, ECD, DY, and CL

Transaction type	**Time (Minutes)**				
	T	**CHY**	**ECD**	**DY**	**CL**
Gate queueing time	30	5	5	5	5
Time to pick up a loaded container	30	NA	NA	10	5
Time to drop off a loaded container	20	NA	NA	10	5
Time to pick up an empty container	15	NA	10	NA	5
Time to drop off an empty container	10	NA	10	NA	5
Swapping chassis	25	15	NA	NA	NA
Time to pick up chassis	15	10	NA	NA	NA
Time to drop off chassis	10	5	NA	NA	NA

For double moves (e.g. returning an empty container and picking up an import container on the same trip), the transaction time was assumed to be the summation of transaction times, plus one queuing time. The lower bound of time windows was assumed to be uniformly distributed in the range of 0 (8:00 A.M.) to 240 (12:00 P.M.) and the upper bound was calculated according to the width of the time window. The width of the time window was assumed to be 240 minutes. It was assumed that the marine terminal and the off-terminal chassis yard/empty container depot/drop yard are 10 minutes apart. The ratio of 20-ft containers to 40-ft containers was assumed to be 25:75 to reflect the approximate current 20-ft to 40-ft container ratio in the U.S. (NCFRP Report 20).

Based on the location of the chassis yard, empty container depot, import pickup, and export delivery, 12 configurations were considered as shown in Figure 5.4. Note that Configurations 1 to 4 (Figures 5.4a-5.4d) are associated with Scenario 1, Configurations 5 to 8 (Figures 5.4e-5.4h) are associated with Scenario 2, and Configurations 9 to 12 (Figures 5.4i-5.4l) are associated with Scenario 3.

An experimental design was set up to study the effect of the aforementioned scenarios on drayage operation time. One type of experimental design is factorial experimental design (FED). In FED, first, a set of "factors" is selected which consists of the variables that are chosen to be studied. Then, these factors are systematically set to predefined discrete values, known as "levels." In FED, combinations of all levels of factors are considered, and then the effect of each combination on the output is studied.

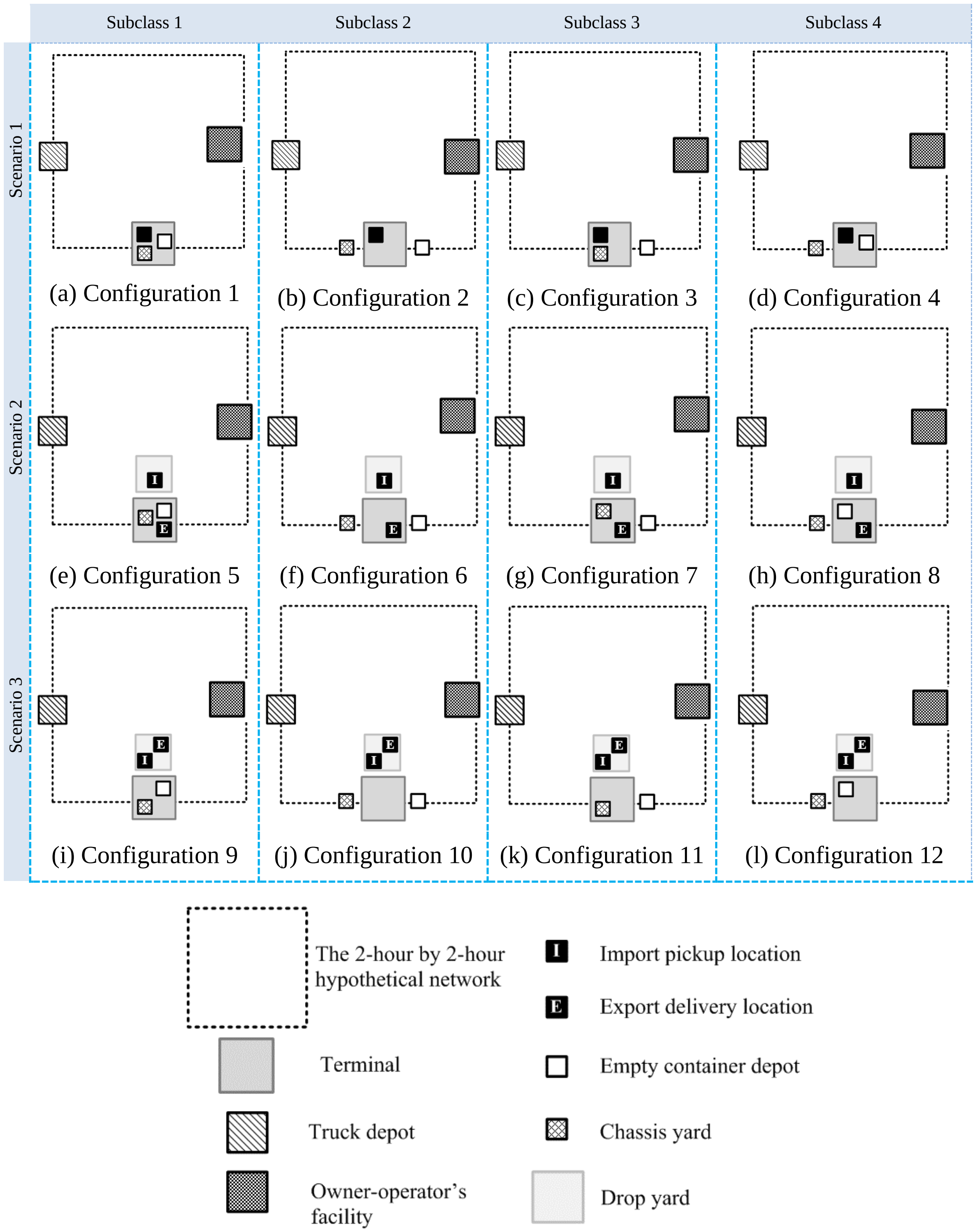


Figure 5.4 Location of the marine terminal and second-tier facilities considered in experiments

In this study, the factors considered, and their levels are as follows.

1. Problem size in terms of number of job nodes (PS)

   Levels: (1) 60, and (2) 100

2. Scenario (S)

   Levels: (1) Scenario 1, (2) Scenario 2, and (3) Scenario 3

3. Empty container depot location (ECL)

   Levels: (1) inside the terminal (ONEC), and (2) outside the terminal (OFFEC)

4. Chassis yard location (CHSS)

   Levels: (1) inside the terminal (ONTY), (2) outside the terminal in (OFFTY)

5. Percent of job nodes: % of empty container delivery nodes, % of loaded container delivery nodes, % of empty container pickup nodes, % of loaded container pickup nodes (PJN):

   Levels: (1) 25:25:25:25, and (2) 15:35:35:15

The combination of factors and levels result in a 2×3×2×2×2 factorial design which yields a total of 48 problem classes. For each problem class, three instances are randomly generated which yields 144 experiments. The 25:25:25:25 is equivalent to the typical percent of job nodes at the Port of Oakland's terminal gate transactions, and the 15:35:35:15 is equivalent to the typical percent of job nodes at Port of Long Beach's terminal gate transactions, based on available data.

To facilitate the presentation of the results, the combination of factors (3 and 4) and their levels are grouped into subclasses, as outlined below.

Subclass 1. ONEC and ONTY (Configurations 1, 5 and 9 shown in Figure 5.4)
Subclass 2. OFFEC and OFFTY (Configurations 2, 6 and 10 shown in Figure 5.4)
Subclass 3. OFFEC and ONTY (Configurations 3, 7 and 11 shown in Figure 5.4)
Subclass 4. ONEC and OFFTY (Configurations 4, 8 and 12 shown in Figure 5.4)

The subclasses are illustrated in Figure 5.4 by the dashed blue lines. Note that for subclass 1, both the chassis yard and empty container depot are located inside the marine terminal. For subclass 2, both are located outside the marine terminal. For subclass 3, the chassis yard is located inside the marine terminal and the empty container depot is located outside. Lastly, for subclass 4, the chassis yard is located outside the marine terminal and the empty container depot is located inside.

5.4.2 Experimental Results and Discussion

Figure 5.5 shows the average drayage operation time for all classes. The results are divided into eight groups (denoted as a-h) by the subclasses and percent of job nodes. The subclass and percent of job nodes are shown in the upper right-hand corner of each box. For example, in the group a, the value "1/1" denotes Subclass 1 and percent of job nodes level 1. The asterisks on each box denote the average drayage operation time for classes with 60 job nodes, and the squares on each box denote classes with 100 job nodes. To understand the impact of second-tier facilities, in the following, it may be helpful to recall that Scenario 1 represents the traditional drayage practice where the import and export operations take place inside the marine terminal. Scenario 2 and 3 represent new practices. Import operations take place at the drop yard in Scenario 2, and both import and export operations take place at the drop yard in Scenario 3.

Figures 5.5a-d show the results of classes where the percent of job nodes is equal to 25:25:25:25. Figures 5.5e-h show the results of classes where the percent of job nodes is equal to 15:35:35:15. Based on the experimental results for all the subclasses in Scenario 1, Subclass 1 has the lowest drayage operation time. Based on the experimental results for all the subclasses in Scenario 2, Subclass 2 has the lowest drayage operation time. Similarly, based on the experimental results for all the subclasses in Scenario 3, Subclass 2 has the lowest drayage operation time. Overall, the results of the all set of experiments showed that Scenario 3 with Subclass 2 has the lowest drayage operation time.

Tables 5.5 and 5.6 show the relative ranking of traditional and new practices in placing import pickup and export delivery locations (i.e., scenarios) based on drayage operation time. It may be helpful to recall that in the traditional practice both import pickup and export delivery locations are inside the terminal, and in the new practices, either only import pickup location is at an off-terminal drop yard and export delivery location is inside the terminal, or both import pickup and export delivery locations are at an off-terminal drop yard. Rankings are provided in different configurations of chassis yard and empty container depot locations (i.e., inside and outside the terminal). Tables 5.5 and 5.6 show the results of experiments where the percent of job nodes are 25:25:25:25 and 15:35:35:15, respectively.

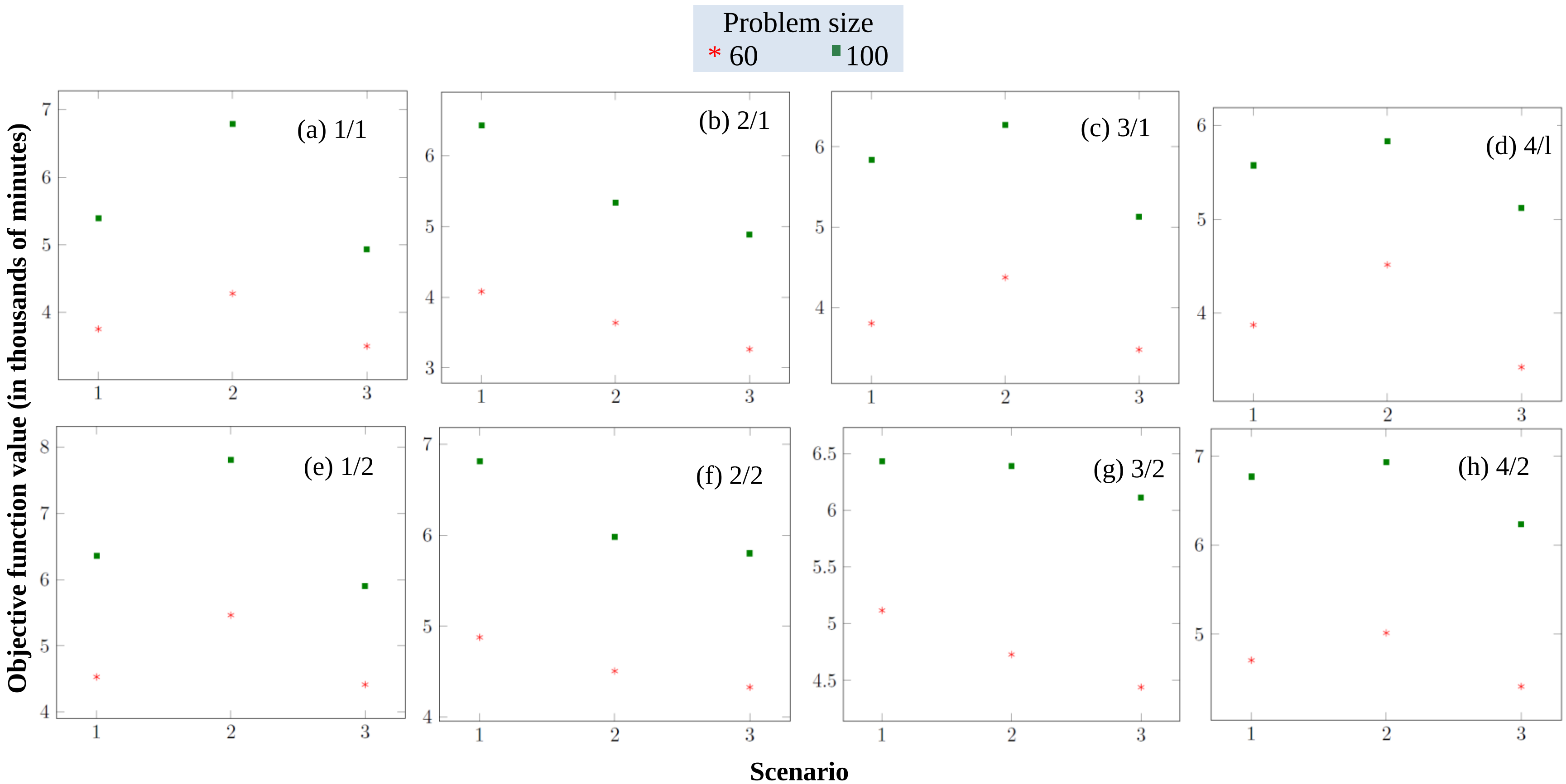


Figure 5.5 Average drayage operation time by scenarios according to subclass/level of percent of job nodes

Results show that the new practice where both import pickup and export delivery locations are at an off-terminal drop yard has the lowest drayage operation time in all configurations of chassis yard and empty container depot locations. From these results, it can be concluded that by moving the locations of both import pickup and export delivery from inside the container terminal to a location outside the terminal, the efficiency of drayage operation would increase. The reason is that the drop yard has shorter queues and shorter turn times compared to the marine terminal, which leads to net improvement in drayage operation efficiency.

- When there are an equal number of empty container delivery, loaded container delivery, empty container pickup and loaded container pickup requests (i.e. the percent of job nodes is 25:25:25:25), traditional practice where both import pickup and export delivery locations are inside the terminal has the second-lowest drayage operation time with configurations where empty container depot and/or chassis yard are located inside the terminal. The reason is that drayage operation efficiency will increase by utilizing double moves inside the terminal in the traditional practice. However, when both empty container depot and chassis yard are located outside the terminal trucks can make fewer double moves inside the terminal. As a result, the new practice where only import pickup location is at an off-terminal drop yard, with shorter queues and shorter turn times compared to the marine terminal, becomes the practice with second-lowest drayage operation time where both chassis yard and empty container location are outside the terminal.

- When the percent of job nodes is 15:35:35:15 (i.e., 15% of empty container delivery nodes, 35% of loaded container delivery nodes, 35% of empty container pickup nodes, 15% of loaded container pickup nodes), the number of customers with empty container pickup and loaded container delivery requests are higher than the number of customers with empty container delivery and loaded container pickup requests. As a result, the locations of empty container depot and import pickup play a critical role in the efficiency of drayage operation (i.e., whether or not both are inside the terminal). Traditional practice where both import pickup and export delivery locations are inside the terminal has the second-lowest operation time with the configurations in which the empty container depot is inside the terminal. The reason is that in this practice trucks can make double moves inside the marine terminal, picking up import containers after delivering empty containers (the percentage of both is 35%) which improves drayage efficiency and makes this scenario more efficient where empty containers are located inside the terminal. The new practice where only import pickup location is at an off-terminal drop yard and export delivery location is inside the terminal has the second-lowest operation time in configurations where empty container depot is located outside the terminal. The reason is that in this practice, import pickup location is outside the terminal and trucks can make less double moves inside the terminal. Instead, the shorter queues and shorter turn times at the drop yard and the off-terminal empty container depot play a critical role in the efficiency of drayage operation in this scenario and make it more efficient in the configurations where the empty container depot is located outside the terminal.

Table 5.5 The relative ranking of traditional and new practices in placing import pickup and export delivery locations (i.e., scenarios) based on drayage operation time where percent of job nodes is 25:25:25:25

				On-terminal import pickup and export delivery locations	Off-terminal import pickup and on-terminal export delivery locations	Off-terminal import pickup and export delivery locations
Chassis yard	On-terminal	Empty Container Depot	On-terminal	Second-lowest	Highest	Lowest
			Off-terminal	Second-lowest	Highest	Lowest
	Off-terminal	Empty Container Depot	On-terminal	Second-lowest	Highest	Lowest
			Off-terminal	Highest	Second-lowest	Lowest

Table 5.6 The relative ranking of traditional and new practices in placing import pickup and export delivery locations (i.e., scenarios) based on drayage operation time where percent of job nodes is 15:35:35:15

				On-terminal import pickup and export delivery locations	Off-terminal import pickup and on-terminal export delivery locations	Off-terminal import pickup and export delivery locations
Chassis yard	On-terminal	Empty Container Depot	On-terminal	Second-lowest	Highest	Lowest
			Off-terminal	Highest	Second-lowest	Lowest
	Off-terminal	Empty Container Depot	On-terminal	Second-lowest	Highest	Lowest
			Off-terminal	Highest	Second-lowest	Lowest

Table 5.7 shows the most efficient locations for empty container depot and chassis yard in traditional and new practices of placing import pickup and export delivery locations in the U.S. When both import pickup and export delivery locations are inside the terminal, the most efficient locations for empty container depot and chassis yard are inside the terminal. The reason is that with chassis, empty containers, import containers and export containers being stored at the terminal, trucks can drop off a chassis/empty container/loaded container and then pick up a chassis/empty container/loaded container on the same trip. When import pickup and/or export delivery locations are at drop yard, the most efficient locations for the chassis yard and empty container depot is outside the terminal. The reason is that when import and/or export containers are located outside the terminal, the truck cannot make double moves for import pickup and/or export delivery inside the terminal. Instead, by locating both empty container depot and chassis yard outside the terminal, drayage operation efficiency will increase as these facilities have a shorter queue and shorter turn times compared to the marine terminal. The results suggest that there is a logic to facility grouping. The chassis pools and container depots are most efficiently located with the last mile deliveries and pickups. If the driver who will deliver the import container to the consignee comes to the marine terminal, then the chassis and container depots should be there too. However, if that driver picks up the import container at an off-terminal drop yard, the empty container depot and chassis yard should be at the off-terminal locations as well.

Table 5.7 The best locations for placing empty container depot and chassis yard according to locations of import pickup and export delivery

	On-terminal import pickup and export delivery locations	Off-terminal import pickup and on-terminal export delivery locations	Off-terminal import pickup and export delivery locations
Empty Container Depot	On-terminal	Off-terminal	Off-terminal
Chassis Yard	On-terminal	Off-terminal	Off-terminal

Finally, Table 5.8 shows the impact of new practices in using second-tier facilities on drayage efficiency. The results answer this question: "What is the average percentage change in drayage operation time between traditional model and second-tier facility models?" Each cell of Table 5.8 contains the average percentage of change in drayage operation time when going from traditional practice in the U.S. (i.e., the locations of import pickup, export delivery, chassis yard and empty container depot are inside the terminal) to one of the new practices in using second-tier facilitates. Green cells show situations that the drayage operation efficiency increases and red cells show situations that the drayage operation efficiency decreases.

The results show, in the traditional practice, by moving the location of empty container depot to a location outside the terminal, drayage operation time increased by 6% on average. Similarly, by moving the location of chassis to a location outside the terminal, drayage operation time increase 4% on average. When both empty container depot and chassis yard are moved to outside the terminal drayage operation time increased by 11% on average.

Table 5.8 The average percentage change in drayage operation time when moving from the traditional model to one of the second-tier facility models

				On-terminal import pickup and export delivery locations	Off-terminal import pickup and on-terminal export delivery locations	Off-terminal import pickup and export delivery locations
Chassis yard	On-terminal	**Empty Container Depot**	On-terminal	-	21%	-6%
			Off-terminal	6%	9%	-5%
	Off-terminal	**Empty Container Depot**	On-terminal	4%	12%	-4%
			Off-terminal	11%	-2%	-9%

Also, for the scenario in which the drop yard is used for import only, drayage operation time increased by 21% on average where both chassis yard and empty container are located inside the terminal. Drayage operation time increased by 9% on average where chassis yard is located inside the terminal and empty container are located outside the terminal. Also, drayage operation time increased by 12% where chassis yard is located outside the terminal and empty container depot is located inside the terminal. However, when both chassis yard and empty container depot are located outside the terminal drayage operation time decreased by 2%.

Finally, the results show that in all configurations of empty container depot and chassis yard locations, moving both import pickup and export delivery locations to outside the terminal will improve drayage operation time between 4% and 9% on average.

5.5 SUMMARY AND CONCLUSION

This paper builds on the authors' previously drayage scheduling model to study the impact of second-tier facilities on drayage operation time. This model is modified by incorporating these features: (1) trucks do not have to wait at customers' locations during the import unloading and export loading operations; (2) drayage operations can include a drop yard (i.e., second-tier facility) for picking up or/and dropping off loaded containers outside the marine container terminal; and (3) a customer is allowed to request any of the following jobs: pick up an empty container, pick up a loaded container, drop off an empty container, or drop off a loaded container. The results indicated that: (1) moving the location of both import pickup and export delivery from inside the marine container terminal to a location outside the terminal could increase the efficiency of drayage operation; the key factors in these drayage efficiency gains are the shorter queues and truck turn times that are typical of second-tier facilities; (2) when import pickup and export delivery take place inside the marine container terminal, the most efficient location for the chassis yard and empty container depot is inside the terminal; and (3) when the location of import pickup and/or export delivery are outside the terminal, the most efficient location for the chassis yard and empty container depot is also outside the terminal.

This study has a few limitations that need to be taken in account when interpreting the aforementioned results: (1) the drayage problem was considered as a deterministic problem, and hence, it did not account for uncertainty in operation times and travel times; (2) it did not consider cases where trucks need to be rerouted due to accidents or road closure; and (3) the results are based on a hypothetical network with aforementioned configuration and characteristics.

The potential drayage efficiencies depend heavily on the shorter queuing and handing ("turn") times at less-complex second-tier facilities as compared to marine container terminals. The difference is due to both complexity and congestion, and if second-tier facilities become more complex the truck turn times could rise and reduce the advantages.

Most second-tier facilities have been created as reserve capacity for marine terminals or as buffers to reconcile the preferred delivery times of importers with the available gate hours of marine terminals. The modeling results suggest that these facilities could also yield operational savings.

Finally, the modeling results suggest that the observed evolution of North American marine container terminals from self-contained entities into multi-tier systems is consistent with overall drayage efficiency. This finding has important implications for regions and communities concerned over the impact of growing container ports and containerized cargo.

ACKNOWLEDGMENT

This paper is based upon work supported by the National Science Foundation under Grant no. 1100227.

CHAPTER 6: INTEGRATED DRAYAGE SCHEDULING PROBLEM WITH STOCHASTIC CONTAINER PACKING AND UNPACKING TIMES[5]

[5] Shiri, S., Ng, N, Huynh, N., Integrated Drayage Scheduling Problem with Stochastic Container Packing and Unpacking Times. Accepted to publish in Journal of the Operational Research Society.

ABSTRACT

This paper considers the integrated drayage scheduling problem. Two new models are developed that account for the uncertainty of (un)packing times in drayage operation without an explicit assumption about their probability distributions. These models are developed for situations when an accurate probability distribution is not available. The first model requires the specification of the mean and variance of the (un)packing times, and the second model requires the specification of mean and upper and lower bounds of the (un)packing times. To demonstrate the feasibility of the developed models, they are tested on problem instances with real-life characteristics. The numerical results show that the drayage operation time increases when the mean of (un)packing times, the variance of the (un)packing times, or the user-specified confidence level is increased. Also, the results indicate that the stochastic models produce schedules that are more likely to be feasible under a variety of scenarios compared to the deterministic model.

6.1 INTRODUCTION

Macharis and Bontekoning (2004) define intermodal freight transport as the transportation of freight in an intermodal container using at least two transport modes. Figure 6.1 illustrates the logistical process of bringing goods from overseas to the market in the U.S. via intermodal transportation. First, an empty container is transported from an empty container depot or from another customer's location to the shipper's location (step 1) where goods are packed into the container (step 2); the use of containers facilitates the transfer of cargo between transport modes. Then the container is "drayed" (i.e., transported) to a marine container terminal by a truck (step 3) where it will get full onto a container vessel (step 4). Next, the container vessel sails to its next port of destination (step 5). Once the vessel reaches its destination port, the container is unloaded and stored at the container terminal (step 6) before it gets "drayed" off to the consignee (step 7). At the consignee's location, the container is first unpacked (step 8), and then the truck returns the empty container to the empty container depot or transports it to another customer's location (step 9). Steps 1, 3, 7, and 9 are known as drayage and they are an integral part of the intermodal freight transportation system. A similar intermodal transport process takes place for domestic goods. The only difference is that instead of using the vessel to transport the containers between two terminals that are significantly far apart, a train is used instead. In the U.S., for domestic goods, intermodal transport is often used when the two terminals are 750 miles apart or greater (FHWA-PL).

As mentioned, drayage operations involve transporting full and empty containers. Typically, to optimize drayage operation, two problems are considered: empty container allocation problem and vehicle routing problem. The objective of the empty container allocation problem is to determine the optimal distribution of empty containers based on the locations of demand and supply (i.e., customer locations, container terminal and empty container depot). The objective of the vehicle routing problem is to determine the optimal tours for trucks to satisfy the pickup and delivery orders of full and empty containers. Traditionally, these two problems are solved in a sequential manner. That is, first the empty container allocation problem is solved to determine the movement of empty containers based on supply and demand. Then, the routing problem is solved to determine the tours for trucks to satisfy the pickup and delivery orders of full and empty containers. Readers are referred to the work of Chang et al. (2008), Braekers et al. (2011) and Song and Dong

(2015) for a technical description of the empty container allocation problem. If it is assumed that vehicle capacity equals one and the drayage operation involves picking up or dropping off only one container at a time, then the vehicle routing problems applied to model drayage operations will be a variation of the pickup-and-delivery problem (PDP). Readers are referred to the work of Wang and Regan (2002), Ileri et al. (2006), Imai et al. (2007) and Nossack and Pesch (2013) for a comprehensive review of studies that formulated the drayage scheduling problem as a PDP.

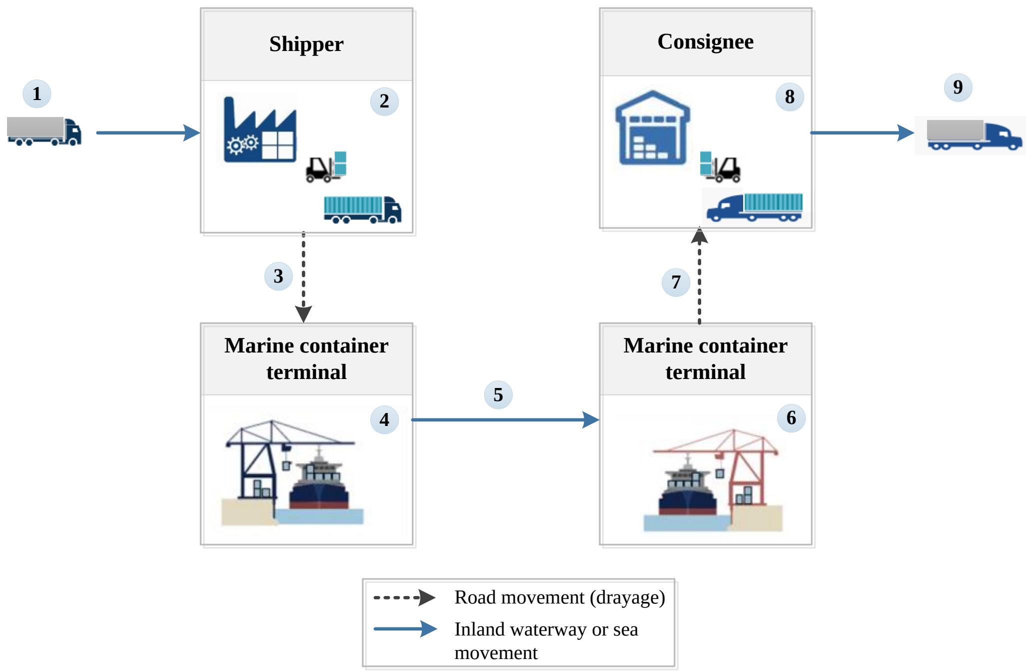


Figure 6.1 Illustration of intermodal transport (images were taken from Fremantle Ports, Iliadis Transports SA, Logistics Executive, Seaboard Foods and Zetes Corporate websites)

Recently, a number of studies have sought to solve the empty container allocation problem and vehicle routing problem jointly (referred to as an integrated model). These studies include the work of Zhang et al. (2009; 2010; 2011) and Braekers et al. (2013;

2014). Zhang et al. (2009) and (2010) formulated the integrated model as a multiple traveling salesman problems with time windows (m-TSPTW). Zhang et al. (2009) proposed a meta-heuristics based on RTS to solve the problem and Zhang et al. (2010) developed a window-partition based solution method. Zhang et al. (2011) further extended their previous work by assuming that the number of empty containers at the depot is limited. Braekers et al. (2013) used both sequential and integrated approaches to solve the drayage problem. The authors proposed a single-phase and a two-phase deterministic annealing algorithm to solve their proposed models. Braekers et al. (2014) extended their previous work by considering an objective function with two objectives: minimizing the number of vehicles and minimizing the total distance. Shiri and Huynh (2016) extended the work of Zhang et al. (2010) by considering the truck appointment system and drayage scheduling problem jointly. The authors solved the empty container allocation problem, vehicle routing problem and appointment booking problem in an integrated manner. In their subsequent work, Shiri and Huynh (2017) extended their integrated model by considering 1) chassis as a separate resource, 2) different container sizes, and 3) scenarios where drayage companies can subcontract the work to independent owner-operators. Their integrated model is the first to solve the scheduling of tractors, full containers, empty containers, and chassis jointly.

In recent years, a number of drayage studies have explicity considered different container sizes. These studies include the work of Vidović et al. (2011, 2012), Popović et al. (2014), Funke and Kopfer (2016) and Shiri and Huynh (2017). Vidović et al. (2011) addressed the drayage problem as a multiple matching problem. They proposed a heuristic approach based on matching utilities to solve their proposed model. Vidović et al. (2012)

proposed two mathematical formulations for the multi-container-size drayage problem: 1) multiple assignment formulations, and 2) general mixed integer programming formulation. The works of Vidović et al. (2011, 2012) were extended by Popović et al. (2014) to consider time windows in drayage operation. The authors developed a variable neighborhood search heuristic to solve their model. Funke and Kopfer (2016) also considered different container sizes in their drayage study. The authors developed a mixed-integer linear programming model and used CPLEX to solve small-sized problems.

The majority of the drayage studies in the literature has focused on the static and deterministic version of the drayage scheduling problem to keep the models tractable. Very few studies have considered uncertainty in drayage operations and thereby addressed the stochastic version of the drayage scheduling problem. Cheung and Hange (2003) addressed uncertainty in task durations and formulated the problem as a "stochastic dynamic model." The objective function of their developed model minimizes the costs of the current driver-task assignment and the expected future cost. To estimage the future cost, the authors developed a "time-window sliding" solution procedure. Cheung et al. (2005) also assumed uncertainty in task duration and formulated the problem as a dynamic decision model. The authors developed an adaptive labeling solution procedure to solve their proposed model. Máhr et al. (2010) assumed uncertainty in service-times and job-arrivals to PDP and developed two solution approaches, an agent-based method, and an online optimization method. The authors found that the agent-based method outperforms the online optimization method in those scenarios that have moderate service time and job-arrival uncertainties. Marković et al. (2014) proposed a model that takes into consideration uncertainty in truck-rail intermodal transport. The sources of uncertainties are truck roundtrip durations and unknown train departure times. Their proposed model is designed to minimize the expected cost which consists of 1) expected storage cost, 2) expected in-terminal operation cost, and 3) expected penalty cost for late delivery. The authors proposed two solution methods: 1) local search based on the interior point method, and 2) a hybrid genetic algorithm.

In recent years, a number of drayage studies have explicity considered different container sizes. These studies include the work of Vidović et al. (2011, 2012), Popović et al. (2014), Funke and Kopfer (2016) and Shiri and Huynh (2017). Vidović et al. (2011) addressed the drayage problem as a multiple matching problem. They proposed a heuristic approach based on matching utilities to solve their proposed model. Vidović et al. (2012) proposed two mathematical formulations for the multi-container-size drayage problem: 1) multiple assignment formulations, and 2) general mixed integer programming formulation. The works of Vidović et al. (2011, 2012) were extended by Popović et al. (2014) to consider time windows in drayage operation. The authors developed a variable neighborhood search heuristic to solve their model. Funke and Kopfer (2016) also considered different container sizes in their drayage study. The authors developed a mixed-integer linear programming model and used CPLEX to solve small-sized problems.

A few studies have addressed the dynamic version of the drayage scheduling problem. Zhang et al. (2011) proposed a solution approach that involves solving the drayage problem at the beginning of the planning horizon using the available information at the time, and then resolving the problem at several different decision epochs using the updated information. Escudero et al. (2011; 2013) proposed a dynamic approach that involves taking snapshots of prevailing situations and using the real-time knowledge about the position of the vehicles and then re-running the optimization model. Zhang et al. (2014) assumed flexible orders in their work. The authors provided two strategies for solving the problem when interruptions occur: 1) append, and 2) re-optimization. The append strategy assigns newly arrived orders to trucks, and the re-optimization strategy re-solves the drayage problem with updated information.

This paper considers the integrated drayage scheduling problem in which a truck can carry only one 40-ft container. It builds on our previous work and extends the integrated drayage scheduling model to consider uncertainty in service time. Specifically, the (un)packing times of containers at customer locations are assumed to be uncertain. Recognizing the inherent difficulty with obtaining an accurate probability distribution for the (un)packing times, this paper develops two new stochastic drayage scheduling models without an explicit assumption about the probability distributions of (un)packing times. The first model assumes that only the mean and variance of the (un)packing times are available, and the second model assumes that the mean and upper and lower bounds of the (un)packing time are available. To solve this model, a reactive tabu search algorithm (RTS) combined with an insertion heuristic developed by the authors is used.

6.2 PROBLEM DESCRIPTION AND FORMULATION

6.2.1 Drayage Problem Description and Assumptions

The aim of this study is to address the scheduling decision to be made by a drayage company on a daily basis. That is, the optimal schedule of trucks in drayage operation which minimizes the drayage operation time is determined. The drayage company is considered to have a limited number of trucks and multiple truck depots. It is assumed that trucks are identical and initially located at the truck depots and should return to one of the company's depots. Also, it is assumed that trucks can only return to the depot upon completion of their assigned tasks/routes; that is, trucks cannot return to the depot and start a new route during the planning span. Drayage operation is assumed to involve one of the following jobs: import pickup job or export delivery job. A customer is allowed to request one or more of the aforementioned two jobs. For each type of job, a series of activities need to be completed. These include: 1) activities that should be performed for each type of job at the customer location such as (un)packing, 2) activities that should be performed for each type of job between the customer location and terminal and at the terminal such as travel to the terminal from a customer location, and 3) activities that should be performed after the completion of one job and before the commencement of the next job such as returning the empty container to the empty container depot after completing the import pickup job and before starting another import pickup job.

It is assumed that all containers (empty and full) are of the same type (40-ft dry containers). It is assumed that a sufficient number of empty containers are stored at an empty container depot located outside the terminal. Empty containers should be picked up from and delivered to this depot. It is assumed that full containers are stored at the terminal and should be picked up from and delivered to the terminal. In this study, it is assumed that trucks should stay at the customers' locations during the (un)packing operation; this assumption has been made in many other drayage studies, such as Zhang et al. (2010, 2011) and Escudero et al. (2011, 2013).

It is assumed that all containers (empty and full) are of the same type (40-ft dry containers). It is assumed that a sufficient number of empty containers are stored at an

empty container depot located outside the terminal. Empty containers should be picked up from and delivered to this depot. It is assumed that full containers are stored at the terminal and should be picked up from and delivered to the terminal. In this study, it is assumed that trucks should stay at the customers' locations during the packing and unpacking operation; this assumption has been made in many other drayage studies, such as Zhang et al. (2010, 2011) and Escudero et al. (2011, 2013).

6.2.2 Notation

The notations used to describe drayage scheduling problem are provided in Table 6.1.

Table 6.1 Drayage model notations

Notation	Notation description
N_D	Set of truck depot nodes
N_I	Set of import job nodes
N_E	Set of export job nodes
N_J	Set of job nodes, $\{N_I \cup N_E\}$
T	Set of time periods at terminal
n_i	Number of trucks initially located at depot *i*
$[L_i, U_i]$	Time window of job node *i*
$[L_k^T, U_k^T]$	Time period *k* at terminal
Q_k	Number of terminal specified appointment quotas for each time period *k* (time period *k*'s capacity)
TT_{ij}	Transfer time on arc (*i, j)*
$\tilde{ST}_i$	Stochastic service time of node *i*
ST_{Ii}	Expected service time of import job nodes *i*
ST_{Ei}	Expected service time of export job nodes *i*
$\tilde{t}_i$	Stochastic total time of all activities before starting node *i*'s destination activities
t_i	Expected total time of all activities before starting node *i*'s destination activities
α, β and γ	Values between 0 and 1

6.2.3 Model Formulation

Consider a network that is represented by a directed graph with a set of N nodes and a set of A arcs. The N nodes consist of either a depot node or a job node. A depot node (N_D) specifies the number of trucks at the truck depot, denoted by n_i. A job node is defined as a series of activities that should be performed for each type of job, import pickup (N_I) or export delivery (N_E). The time it takes to complete all of these activities is called the service time (ST_i). The service times associated with import and export job nodes are provided in Table 6.2.

t_i is an attribute of job nodes that indicates the total time of all activities before starting node i's destination activities. For the import job node, the destination is the consignee's location, and thus, t_i is the combined time associated with activities 1 and 2 shown in Table 6.2. For the export job node, the destination is the container terminal and thus, t_i is the combined time associated with activities 1, 2, 3, 4 and 5 shown in Table 6.2.

Table 6.2 Service time associated with import and export job nodes

Job Node *i*	**Activities and Time**
$i \in N_I$	1. Pick up import container at terminal (terminal turn time). 2. Transport container to customer (travel time between terminal and customer's location). 3. Unmount full container from truck (time to unmount container). 4. Customer unpack container (unpack time). 5. Mount empty container to truck (time to mount container).
$i \in N_E$	1. Unmount empty container from truck (time to unmount container). 2. Customer pack container (time to pack container). 3. Mount full container to truck (time to mount container). 4. Transport full container to terminal (travel time between customer's location and terminal). 5. Wait in queue at terminal gate (gate queuing time). 6. Drop off export container at terminal (terminal turn time).

Table 6.3 Transfer time for all possible combinations of activities at node i and node j

TT_{ij}		*To node j*		
		N_D	N_I	N_E
From node i	N_D	-	1. Travel time between TD_i[1] and T[2] 2. Gate queuing time	1. Travel time between TD_i and ECD[3] 2. Time to mount container. 3. Travel time between ECD and CL_j[4]
	N_I	1. Travel time between CL_i and ECD 2. Time to unmount container 3. Travel time between ECD and TD_j	1. Travel time between CL_i and ECD 2. Time to unmount container 3. Travel time between ECD and T[4] 4. Gate queuing time	*If node i customer is different from node j customer:* Travel from CL_i to CL_j *Otherwise:* No activity
	N_E	1. Travel time between T and TD_j	No activity	1. Travel time between T and ECD 2. Time to mount container 3. Travel time between ECD to CL_j

[1]TD_i: Truck depot *i* [2]T: Terminal [3]ECD: Empty container depot [4]CL_j: Customer *j*'s location

Time window, denoted by $[L_i, U_i]$ is another attribute of the job nodes which indicates the time interval that activities at this node should start within.

The arc (i, j) represents the transfer time between the completion of node *i* activities and the commencement of node *j* activities. The transfer time on the arc (i, j) depends on the combination of depot and job nodes that occur at *i* and *j*. The transfer time for all possible combinations is provided in Table 6.3.

In this paper, it is assumed that the packing and unpacking times are uncertain. As a result, ST_i and t_i of job nodes have a non-deterministic value. More specifically, it is assumed that their values follow some underlying distributions; however, the exact probability distribution is unknown.

6.3 MATHEMATICAL FORMULATION

The decision variables, objective function, and constraints are presented below.

$$x_{ij} = \begin{cases} 1 & \text{If arc}(i,j) \text{ is included in the solution} \\ 0 & \text{Otherwise} \end{cases}$$

$$q_{ik} = \begin{cases} 1 & \text{If customer } i \text{ books an appoinment in time period } k \\ 0 & \text{Otherwise} \end{cases}$$

s_i = Time that the first activity on node i is started.

$$\min \sum_{i\in N_J}\sum_{j\in N_D} s_i \times x_{ij} - \sum_{i\in N_D}\sum_{j\in N_J} s_j \times x_{ij} + \sum_{i\in N_D}\sum_{j\in N_J} TT_{ij} \times x_{ij} + \sum_{i\in N_I}\sum_{j\in N_D} (ST_{Ii} + TT_{ij}) \times x_{ij} + \sum_{i\in N_E}\sum_{j\in N_D} (ST_{Ei} + TT_{ij}) \times x_{ij} \qquad (6.1)$$

$$\sum_{j\in N_J} x_{ij} \le n_i \qquad \forall i \in N_D \qquad (6.2)$$

$$\sum_{i\in N_D\cup N_J} x_{ij} = \sum_{i\in N_D\cup N_J} x_{ji} = 1 \qquad \forall j \in N_J \qquad (6.3)$$

$$Pr(s_i + \tilde{ST}_i + TT_{ij} - (1 - x_{ij}) \times M \le s_j) \ge 1 - \alpha \qquad \forall i \in N_I, j \in N_J \qquad (6.4)$$

$$Pr(s_i + \tilde{ST}_i + TT_{ij} - (1 - x_{ij}) \times M \le s_j) \ge 1 - \beta \qquad \forall i \in N_E, j \in N_J \qquad (6.5)$$

$$TT_{ij} - (1 - x_{ij}) \times M \le s_j \qquad \forall i \in N_D, \forall j \in N_J \qquad (6.6)$$

$$L_i \le s_i \le U_i \qquad \forall i \in N_J \qquad (6.7)$$

$$s_i - M \times (1 - q_{ik}) \le U_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_I \qquad (6.8)$$

$$s_i + M \times (1 - q_{ik}) \geq L_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_I \qquad (6.9)$$

$$Pr(s_i + \tilde{t}_i - M \times (1 - q_{ik}) \leq U_k^T) \geq 1 - \gamma \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.10)$$

$$Pr(s_i + \tilde{t}_i + M \times (1 - q_{ik}) \geq L_k^T) \geq 1 - \gamma \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.11)$$

$$\sum_{k \in T} q_{ik} = 1 \qquad \forall i \in N_J \qquad (6.12)$$

$$\sum_{i \in N_J} q_{ik} \leq Q_k \qquad \forall k \in T \qquad (6.13)$$

Equation (6.1) is the objective function that seeks to minimize the expected drayage operation time. The first and second terms in the objective function are the start times of a truck's last and first jobs, respectively. The difference between these two times yields the drayage operation time between the first and last jobs. The third term is the drayage operation time between the initial truck depot and the location of the truck's first job. The fourth term includes the service time of the truck's last job and transfer time between the location of the last job and the nearest truck depot. Constraint (6.2) is the capacity constraint for truck depots. This constraint guarantees that the number of routes started from each truck depot is less than or equal to the number of trucks initially were located at that depot. Constraint (6.3) ensures that each customer is visited exactly once. Constraints (6.4), (6.5) and (6.6) enforce the time relationship among consecutive nodes along a route. Constraint (6.4) requires that, with a probability of at least 1-α, job *j* is only scheduled to start once the import job *i* is completed. Similarly, Constraints (6.5) guarantees that, with a probability of at least 1-β, job *j* is only scheduled to start once the export job *i* is completed. Constraint (6.7) restricts the start time of job nodes to their time windows.

Constraints (6.8) and (6.9) determine the time period at which a truck should book an appointment for import job nodes. Constraints (6.10) and (6.11) ensure that, with a probability of at least 1-γ, the booked appointment slot at the terminal can be met, for export job nodes. Constraint (6.12) states that exactly one appointment should be booked for each job node. Constraint (6.13) is the capacity constraint of appointment system which ensures that the number of appointments in each time window to be less than the specified quotas.

In the absence of an exact probability distribution for $\tilde{ST}_i$ and $\tilde{t}_i$, the above model cannot be solved. In the following sections, two models without an explicit assumption about the probability distributions of (un)packing times are developed.

MODEL 1: Only the means and standard deviations of $\tilde{ST}_i$ and $\tilde{t}_i$ are available

MODEL 2: Only the means and the lower and upper bounds of $\tilde{ST}_i$ and $\tilde{t}_i$ are available

6.3.1 MODEL 1

First, consider the export nodes for which the packing time is uncertain. Suppose that the mean and variance of $\tilde{t}_i$ are known, with $E[\tilde{t}_i] = t_i$ and $Var[\tilde{t}_i] = \sigma_{ti}^2$, respectively. Furthermore, suppose that the mean and variance of service times ($\tilde{ST}_i$) are given by $E[\tilde{ST}_i] = ST_{Ei}$ and $Var[\tilde{ST}_i] = \sigma_{Ei}^2$ for export job node *i*, respectively. Note that, by definition of $\tilde{t}_i$ and $\tilde{ST}_i$, there holds $\sigma_{Ei}^2 = \sigma_{ti}^2$, which is the variance of the packing time. In the following, we shall only use σ_{Ei}^2.

Next, consider the import nodes for which the unpacking is uncertain. Suppose that mean and variance of service times ($\tilde{ST}_i$) are given by $E[\tilde{ST}_i] = ST_{Ii}$ and $Var[\tilde{ST}_i] = \sigma_{Ii}^2$ for import job node *i*, respectively.

Under the above assumption of limited information on the exact distribution of $\tilde{t}_i$ and $\tilde{ST}_i$, the above model cannot be solved (i.e., it is intractable). As a safe tractable approximation (Ben-Tal et al., 2009), we have Proposition 6.1.

Proposition 6.1 Let $0 < \alpha,\ \beta$ and $\gamma \le 1$. If Constraints (6.4), (6.5), (6.10) and (6.11) are replaced with the constraints:

$$s_i + ST_{Ii} + \sigma_{Ii}\sqrt{(1-\alpha)/\alpha} + TT_{ij} - (1-x_{ij}) \times M \le s_j \qquad \forall i \in N_I, j \in N_J \tag{6.14}$$

$$s_i + ST_{Ei} + \sigma_{Ei}\sqrt{(1-\beta)/\beta} + TT_{ij} - (1-x_{ij}) \times M \le s_j \qquad \forall i \in N_E, j \in N_J \tag{6.15}$$

$$s_i + t_i + \sigma_{Ei}\sqrt{(1-\gamma)/\gamma} - M \times (1-q_{ik}) \le U_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_E \tag{6.16}$$

$$s_i + t_i - \sigma_{Ei}\sqrt{(1-\gamma)/\gamma} + M \times (1-q_{ik}) \ge L_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_E \tag{6.17}$$

then all feasible solutions of the resulting optimization problem satisfy the chance Constraints (6.4), (6.5), (6.10) and (6.11).

Proof For any feasible solution to the resulting optimization problem we have:

$$\Pr(s_i + \tilde{ST}_i + TT_{ij} - (1 - x_{ij}) \times M > s_j) \leq \Pr(\tilde{ST}_i > ST_{Ii} + \sigma_{Ii}\sqrt{(1-\alpha)/\alpha}) \qquad \forall i \in N_I, j \in N_J \qquad (6.18)$$

Using Cantelli inequality (Meester, 2003), it then follows that $Pr(s_i + \tilde{ST}_i + TT_{ij} - (1 - x_{ij}) \times M \leq s_j) \geq 1 - \alpha$. Using the same argument, we have:

$$Pr(s_i + \tilde{ST}_i + TT_{ij} - (1 - x_{ij}) \times M > s_j) \leq Pr(\tilde{ST}_i > ST_{Ei} + \sigma_{Ei}\sqrt{(1-\beta)/\beta}) \leq \beta \qquad \forall i \in N_E, j \in N_J \qquad (6.19)$$

$$Pr(s_i + \tilde{t}_i - M \times (1 - q_{ik}) > U_k^T) \leq Pr(\tilde{t}_i > t_i + \sigma_{Ei}\sqrt{(1-\gamma)/\gamma}) \leq \gamma \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.20)$$

$$Pr(s_i + \tilde{t}_i + M \times (1 - q_{ik}) < L_k^T) \leq Pr(\tilde{t}_i < t_i - \sigma_{Ei}\sqrt{(1-\gamma)/\gamma}) \leq \gamma \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.21)$$

Q.E.D.

6.3.2 MODEL 2

In this section, it is assumed that in addition to the mean, the lower and upper bounds of (un)packing are known. Also, it is assumed that the (un)packing times can be subdivided in smaller subtasks with statistically independent durations. Note that this is without loss of generality since a trivial possibility is to divide the number of (un)packing activity into one subtask. For the moment, we shall explicitly separate the (un)packing times from other activities in a job node service time.

Again, for export job nodes the packing times are uncertain. We can write:

$$\tilde{ST}_i = ST_{Ei}^{1,3,4,5,6} + \sum_{m=1}^{n_E} \tilde{p}_{im} \qquad n_E \geq 1, i \in N_E \tag{6.22}$$

$$\tilde{t}_i = t_{Ei}^{1,3,4,5} + \sum_{m=1}^{n_E} \tilde{p}_{im} \qquad n_E \geq 1, i \in N_E \tag{6.23}$$

where

$ST_{Ei}^{1,3,4,5,6} =$ the summation of time associated with activities 1,3,4,5 and 6 of service time of export node *i*

$t_{Ei}^{1,3,4,5} =$ the summation of time associated with activities 1,3,4 and 5 of service time of export node *i*

$\tilde{p}_{im} =$ stochastic time of *m*-th subtask of packing time of export node *i*

$n_E =$ number of subtasks in packing

Suppose that mean of $\tilde{t}_i$ ($E[\tilde{t}_i]$) is t_{iE} and mean of $\tilde{ST}_i$ ($E[\tilde{ST}_i]$) is ST_{Ei} for an export node. For import job nodes, the unpacking times are uncertain:

$$\tilde{ST}_i = ST_{Ii}^{1,2,3,5} + \sum_{m=1}^{n_I} \tilde{u}_{im} \qquad n_I \geq 1, i \in N_I \tag{6.24}$$

where

$ST_{Ii}^{1,2,3,5} =$ the summation of time associated with activities 1,2,3 and 5 of service time of import node *i*

$\tilde{u}_{im} =$ stochastic time of *m*-th subtask of packing time of import node *i*

$n_I =$ number of subtasks in unpacking

Suppose that mean of $\tilde{ST}_i$ ($E[\tilde{ST}_i]$) is ST_{Ii} for an import node.

Proposition 6.2 Let $Pr(u_{im}^L \le \tilde{u}_{im} \le u_{im}^U) = 1$, $Pr(p_{im}^L \le \tilde{p}_{im} \le p_{im}^U) = 1$ and $0 < \alpha, \beta, \gamma \le 1$. If Constraints (6.4), (6.5), (6.10) and (6.11) are replaced with the constraints:

$$s_i + ST_{Ii} + \sqrt{-\sum_{m=1}^{n_I}(u_{im}^U - u_{im}^L)^2 \ln \alpha \Big/ 2} + TT_{ij} - M \times (1 - x_{ij}) \le s_j \qquad \forall i \in N_I, j \in N_J \qquad (6.25)$$

$$s_i + ST_{Ei} + \sqrt{-\sum_{m=1}^{n_E}(p_{im}^U - p_{im}^L)^2 \ln \beta \Big/ 2} + TT_{ij} - M \times (1 - x_{ij}) \le s_j \qquad \forall i \in N_E, j \in N_J \qquad (6.26)$$

$$s_i + t_{Ei} + \sqrt{-\sum_{m=1}^{n_E}(p_{im}^U - p_{im}^L)^2 \ln \gamma \Big/ 2} - M \times (1 - q_{ik}) \le U_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.27)$$

$$s_i + t_{Ei} - \sqrt{-\sum_{m=1}^{n_E}(p_{im}^U - p_{im}^L)^2 \ln \gamma \Big/ 2} + M \times (1 - q_{ik}) \ge L_k^T \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.28)$$

then all feasible solutions of the resulting optimization problem satisfy the chance Constraints (6.4), (6.5), (6.10) and (6.11).

Proof Note that, by definition, $\tilde{ST}_i = ST_{Ii}^{1,2,3,5} + \sum_{m=1}^{n_I} \tilde{u}_{im}$ and $E[\tilde{ST}_i] = ST_{Ii}$. For any feasible solution to the resulting optimization problem we have:

$$Pr(s_i + \tilde{ST}_i + TT_{ij} - M \times (1 - x_{ij}) > s_j) \qquad \forall i \in N_I, j \in N_J \qquad (6.29)$$

$$= Pr(s_i + ST_{Ii}^{1,2,3,5} + \sum_{m=1}^{n_I} \tilde{u}_{im} + TT_{ij} - M \times (1 - x_{ij}) > s_j) =$$

$$\leq Pr\left(\sum_{m=1}^{n_I} \tilde{u}_{im} > \sum_{m=1}^{n_I} u_{im} + \sqrt{-\sum_{m=1}^{n_I} (u_{im}^U - u_{im}^L)^2 \ln \alpha / 2} \right) \leq \alpha$$

where the last inequality is due to Hoeffding (1963). Likewise, we have:

$$Pr(s_i + \tilde{ST}_{Ei} + TT_{ij} - M \times (1 - x_{ij}) > s_j) \qquad \forall i \in N_E, j \in N_J \qquad (6.30)$$

$$\leq Pr\left(\sum_{m=1}^{n_E} \tilde{p}_{im} > \sum_{m=1}^{n_E} p_{im} + \sqrt{-\sum_{m=1}^{n_E} (p_{im}^U - p_{im}^L)^2 \ln \beta / 2} \right) \leq \beta$$

$$Pr(s_i + \tilde{t}_i - M \times (1 - q_{ik}) > U_k^T) \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.31)$$

$$\leq Pr\left(\sum_{m=1}^{n_E} \tilde{p}_{im} > \sum_{m=1}^{n_E} p_{im} + \sqrt{-\sum_{m=1}^{n_E} (p_{im}^U - p_{im}^L)^2 \ln \gamma / 2} \right) \leq \gamma$$

$$Pr(s_i + \tilde{t}_i + M \times (1 - q_{ik}) < L_k^T) \qquad \forall k \in \mathrm{T}, \forall i \in N_E \qquad (6.32)$$

$$\leq Pr\left(\sum_{m=1}^{n_E} \tilde{p}_{im} < \sum_{m=1}^{n_E} p_{im} - \sqrt{-\sum_{m=1}^{n_E} (p_{im}^U - p_{im}^L)^2 \ln \gamma / 2} \right) \leq \gamma$$

Q.E.D.

Proposition 6.3 The approximation in Proposition 6.2 improves as the value of n_E and n_I increases.

Proof. Since the supports of $\sum_{m=1}^{n_I} \tilde{u}_{im}$ and $\sum_{m=1}^{n_E} \tilde{p}_{im}$ remain unchanged when expressing them as smaller sub-components, Hoeffding's bound will improve with increasing values of n_E and n_I.

Q.E.D.

Propostion 6.4 Let z_1 and z_2 denote the optimal total drayage time resulting from the approximations in Proposition 6.1 and 6.2 (i.e. MODELs 1 and 2), then the following holds. Let:

$$\lambda_1 \equiv \begin{pmatrix} \sigma_{Ii}\sqrt{(1-\alpha)/\alpha} \\ \sigma_{Ei}\sqrt{(1-\beta)/\beta} \\ \sigma_{Ei}\sqrt{(1-\gamma)/\gamma} \end{pmatrix} \tag{6.33}$$

$$\lambda_2 \equiv \begin{pmatrix} \sqrt{-\sum_{m=1}^{n_I}(u_{im}^U - u_{im}^L)^2 \ln\alpha \Big/ 2} \\ \sqrt{-\sum_{m=1}^{n_E}(p_{im}^U - p_{im}^L)^2 \ln\beta \Big/ 2} \\ \sqrt{-\sum_{m=1}^{n_E}(p_{im}^U - p_{im}^L)^2 \ln\gamma \Big/ 2} \end{pmatrix} \tag{6.34}$$

If $\lambda_1 < \lambda_2$, then $z_1 < z_2$. If $\lambda_1 > \lambda_2$, then $z_1 > z_2$. Finally, if $\lambda_1 = \lambda_2$, then $z_1 = z_2$.

Proof. Follows by comparing the feasible regions of the resulting optimization problems.

Q.E.D.

6.4 NUMERICAL EXPERIMENTS

6.4.1 Models Comparison Results

The proposed models are evaluated using the same experimental parameters used in Shiri and Huynh (2016). In both models, it is assumed that $\alpha = \beta = \gamma = 0.05$. Also, it is assumed that the mean of both packing and unpacking times is 32.5 minutes (Zhang et al., 2010). In MODEL 1, the standard deviation of both packing and unpacking times is assumed to be 15.87 minutes (Zhang et al., 2010). Two versions of MODEL 2 were solved:

VER 1: lower bound and upper bounds are 5 and 60 minutes.

VER 2: lower bound and upper bounds are 5 and 70 minutes.

Table 6.4 shows a comparison of the results for developed models. The first column shows the experiment number. The second column shows the problem size in terms of the number of job nodes. The third column shows the objective function values obtained from MODEL 1. Similarly, the fourth and fifth columns report the objective function values obtained from MODEL 2 solving VER 1 and VER 2, respectively. CPLEX was used to solve the models for smaller instances (i.e., Experiments 1 and 2). The RTS algorithm developed in Shiri and Huynh (2016) was used to solve larger instances (i.e., Experiments 3 to 9).

From Equations (6.33) and (6.34) it can be seen that:

$\lambda_{\text{VER1}} < \lambda_{\text{MODEL1}} < \lambda_{\text{VER2}}$

As predicted by Proposition 6.4:

$z_{\text{VER1}} < z_{\text{MODEL1}} < z_{\text{VER2}}$

Table 6.4. Comparison of models' objective function values

(1) Experiment no.	(2) Problem size	(3) Objective function value	(4)	(5)
		MODEL 1	MODEL 2	
			VER 1	VER 2
1	6	1154.3	998.4	1267.7
2	8	1978.6	1733.2	2170.2
3	15	4721.6	4291.6	4895.3
4	20	6913.4	6201	7361.1
5	30	11913.1	10285.3	12339.8
6	40	14113. 3	13886.3	1577.7
7	50	20313	18126.5	22301.8
8	75	26669.4	25284.8	27851.8
9	100	32669.4	29284.8	35027.2

In the other words, the objective function values resulting from VER 2 is higher than that of MODEL 1. On the contrary, the objective function values resulting from VER 1 is lower than that of MODEL 1. These results are in line with Proposition 6.4.

As shown in columns 4 and 5 of Table 6.4, between VER 1 and VER 2, VER 2 yields a higher objective function value. These findings suggest that increasing the difference between the lower bound and upper bound increases the objective function values.

6.4.2 Experimental Design

A factorial experimental design (FED) was set up to study the effect of newly defined parameters in the developed models on drayage operation time. This type of experimental design consists of first selecting two or more variables to examined, known as “factors”. Then, these factors systematically set to predefined discrete values, known as “levels.” Finally, combinations of all levels of factors are considered, and the effect of each combination on the output is studied.

Table 6.5 Description of problem classes for MODEL 1

Cl.[1]	PS	α, β and γ	μ	σ	Cl.	PS	α, β and γ	μ	σ	Cl.	PS	α, β and γ	μ	σ	Cl.	PS	α, β and γ	μ	σ
1	4	0.025	30	1	**28**	8	0.025	30	1	**55**	40	0.025	30	1	**82**	100	0.025	30	1
2	4	0.025	30	5	**29**	8	0.025	30	5	**56**	40	0.025	30	5	**83**	100	0.025	30	5
3	4	0.025	30	10	**30**	8	0.025	30	10	**57**	40	0.025	30	10	**84**	100	0.025	30	10
4	4	0.025	40	1	**31**	8	0.025	40	1	**58**	40	0.025	40	1	**85**	100	0.025	40	1
5	4	0.025	40	5	**32**	8	0.025	40	5	**59**	40	0.025	40	5	**86**	100	0.025	40	5
6	4	0.025	40	10	**33**	8	0.025	40	10	**60**	40	0.025	40	10	**87**	100	0.025	40	10
7	4	0.025	50	1	**34**	8	0.025	50	1	**61**	40	0.025	50	1	**88**	100	0.025	50	1
8	4	0.025	50	5	**35**	8	0.025	50	5	**62**	40	0.025	50	5	**89**	100	0.025	50	5
9	4	0.025	50	10	**36**	8	0.025	50	10	**63**	40	0.025	50	10	**90**	100	0.025	50	10
10	4	0.05	30	1	**37**	8	0.05	30	1	**64**	40	0.05	30	1	**91**	100	0.05	30	1
11	4	0.05	30	5	**38**	8	0.05	30	5	**65**	40	0.05	30	5	**92**	100	0.05	30	5
12	4	0.05	30	10	**39**	8	0.05	30	10	**66**	40	0.05	30	10	**93**	100	0.05	30	10
13	4	0.05	40	1	**40**	8	0.05	40	1	**67**	40	0.05	40	1	**94**	100	0.05	40	1
14	4	0.05	40	5	**41**	8	0.05	40	5	**68**	40	0.05	40	5	**95**	100	0.05	40	5
15	4	0.05	40	10	**42**	8	0.05	40	10	**69**	40	0.05	40	10	**96**	100	0.05	40	10
16	4	0.05	50	1	**43**	8	0.05	50	1	**70**	40	0.05	50	1	**97**	100	0.05	50	1
17	4	0.05	50	5	**44**	8	0.05	50	5	**71**	40	0.05	50	5	**98**	100	0.05	50	5
18	4	0.05	50	10	**45**	8	0.05	50	10	**72**	40	0.05	50	10	**99**	100	0.05	50	10
19	4	0.1	30	1	**46**	8	0.1	30	1	**73**	40	0.1	30	1	**100**	100	0.1	30	1
20	4	0.1	30	5	**47**	8	0.1	30	5	**74**	40	0.1	30	5	**101**	100	0.1	30	5
21	4	0.1	30	10	**48**	8	0.1	30	10	**75**	40	0.1	30	10	**102**	100	0.1	30	10
22	4	0.1	40	1	**49**	8	0.1	40	1	**76**	40	0.1	40	1	**103**	100	0.1	40	1
23	4	0.1	40	5	**50**	8	0.1	40	5	**77**	40	0.1	40	5	**104**	100	0.1	40	5
24	4	0.1	40	10	**51**	8	0.1	40	10	**78**	40	0.1	40	10	**105**	100	0.1	40	10
25	4	0.1	50	1	**52**	8	0.1	50	1	**79**	40	0.1	50	1	**106**	100	0.1	50	1
26	4	0.1	50	5	**53**	8	0.1	50	5	**80**	40	0.1	50	5	**107**	100	0.1	50	5
27	4	0.1	50	10	**54**	8	0.1	50	10	**81**	40	0.1	50	10	**108**	100	0.1	50	10

[1] Class

6.4.2.1 Experimental Results (MODEL 1)

The considered factors and their levels for MODEL 1 are as follows.

Factors and levels

6. Problem size in terms of number of job nodes (PS):
   Levels: (1) 4, (2) 8, (3) 40, and (4) 100
7. α, β and γ:
   Levels: (1) 0.025, (2) 0.05, and (3) 0.1
8. μ of (un)packing time (in minutes):
   Levels: (1) 30, (2) 40, and (3) 50
9. σ of (un)packing time (in minutes):
   Levels: (1) 1, (2) 5, and (3) 10

The combination of factors and levels result in a total of 108 problem classes, as shown in Table 6.5. For each problem class, three instances are randomly generated using the characteristics of that class. Thus, there is a total of 324 instances.

Figure 6.2 shows the average drayage operation time for all classes. The results are divided into twelve groups (denoted as a to l) by the PS and σ. The PS and σ are shown in the upper left-hand corner of each box. For example, in group b, the value "4/5" denotes PS level 4 and σ level 5 minutes. The squares on each box denote the average drayage operation time for classes with α, β and γ level 0.025, the triangles denote the average drayage operation time for classes with α, β and γ level 0.05, and the asterisks denote the average drayage operation time for classes with α, β and γ level 0.1. The results of all set of experiments showed classes with higher μ and higher σ yield higher objective function values. These results correspond to intuition and suggest that increasing the mean and variance of the (un)packing times increases the drayage operation time. Also, the results showed the drayage operation time increases when the required confidence level is increased. It can be concluded that increasing the confidence level of an estimation to be more confident that the scheduling remains feasible will result in higher drayage operating time.

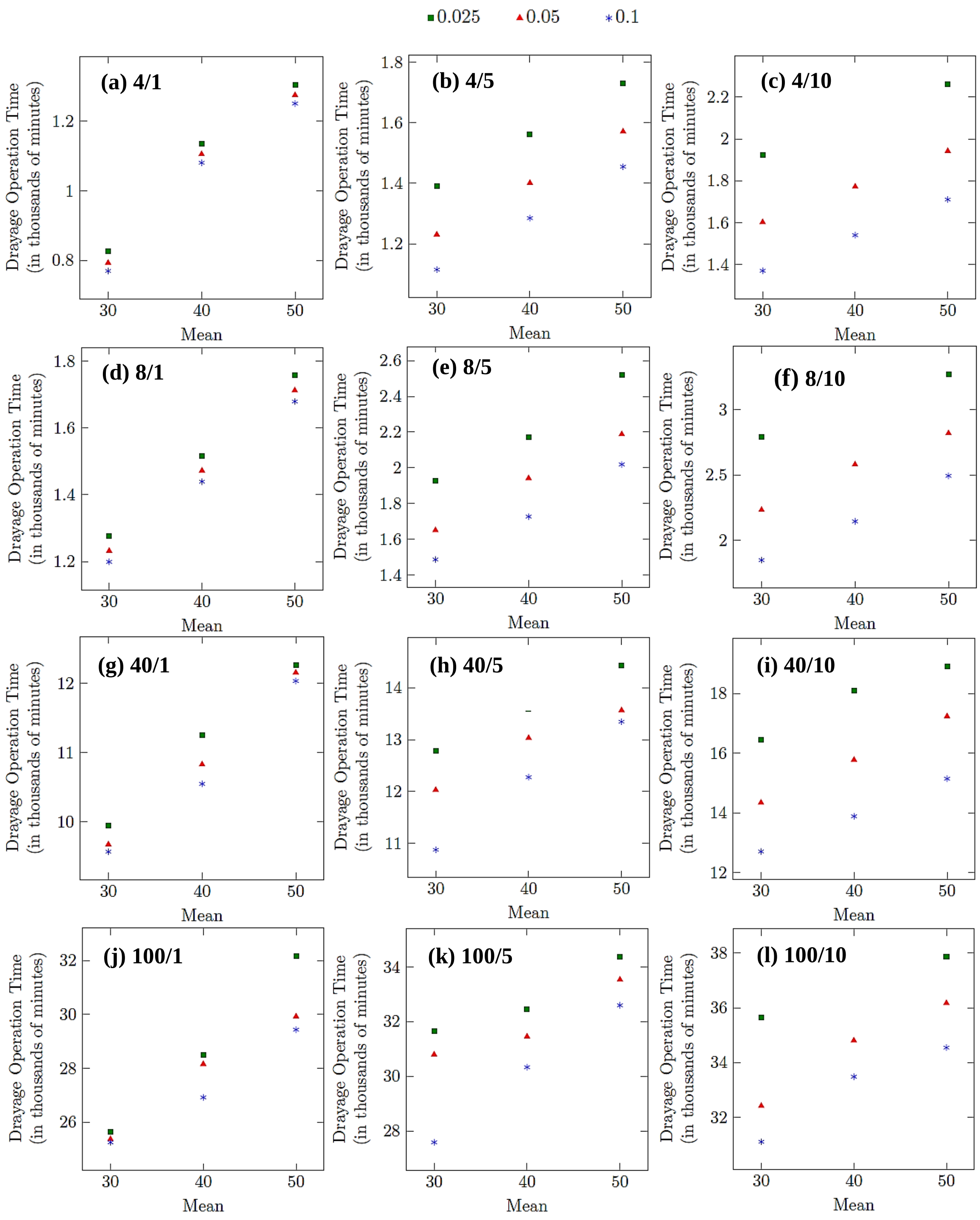


Figure 6.2 Average drayage operation time by mean, according to level of PS/level of σ

6.4.2.2 *Experimental Results (MODEL 2)*

Similar to MODEL 1, a FED is set up for MODEL 2. Two sets of problems are provided in Table 6.6. For each problem, three versions with a different number of subtasks but the same total mean, and lower and upper bounds are defined. For example, in all versions of problem 1, mean is 52 minutes, lower bound is 40 minutes and the upper bound is 80 minutes. But, the number of subtasks is different.

Table 6.6 Characteristics of versions of problems

Problem no.		**Version no. 1**		**2**		**3**	
		b_i[1]	**μ_i[2]**	**b_i**	**μ_i**	**b_i**	**μ_i**
1	**Details of subtasks**	b_1: [10,20]	μ_1: 13	b_1: [5,10]	μ_1: 7	b_1: [5,10]	μ_1: 6
		b_2: [10,20]	μ_2: 13	b_2: [5,10]	μ_2: 7	b_2: [5,10]	μ_2: 7
		b_3: [10,20]	μ_3: 13	b_3: [5,10]	μ_3: 7	b_3: [5,10]	μ_3: 6
		b_4: [10,20]	μ_4: 13	b_4: [5,10]	μ_4: 7	b_4: [5,10]	μ_4: 7
				b_5: [10,20]	μ_5: 12	b_5: [10,20]	μ_5: 7
				b_6: [10,20]	μ_6: 12	b_6: [10,20]	μ_6: 6
						b_7: [5,10]	μ_5: 7
						b_8: [5,10]	μ_6: 6
	T[3]	b: [40,80]	μ: 52	b: [40,80]	μ: 52	b: [40,80]	μ: 52
2	**Details of subtasks**	b_1: [20,30]	μ_1: 22	b_1: [15,20]	μ_1: 16	b_1: [5,10]	μ_1: 6
		b_2: [10,20]	μ_2: 12	b_2: [5,10]	μ_2: 7	b_2: [15,20]	μ_2: 17
		b_3: [10,20]	μ_3: 12	b_3: [10,20]	μ_3: 11	b_3: [5,10]	μ_3: 6
				b_4: [10,20]	μ_4: 12	b_4: [5,10]	μ_4: 6
						b_5: [10,20]	μ_5: 11
	T	b: [40,70]	μ: 46	b: [40,70]	μ: 46	b: [40,70]	μ: 46

[1] b_i: bounds of activity *i* [2] μ_i: mean of activity *i*
[3] T: Total mean, and lower and upper bounds of each version

The considered factors and their levels for MODEL 2 are as follows.

Factors and levels

1. Problem (P):
   Levels: (1) Problem 1, and (2) Problem 2
2. Versions (V):
   Levels: (1) Version 1, (2) Version 2, and (3) Version 3
3. Problem size in terms of number of job nodes (PS)
   Levels: (1) 4, (2) 8, (3) 40, and (4) 100
4. α, β and γ:
   Levels: (1) 0.025, (2) 0.05, and (3) 0.1

The combination of factors and levels result in a total of 72 problem classes, as shown in Table 6.7. For each problem class, three instances are randomly generated using the characteristics of that class. Thus, there is a total of 216 instances.

Table 6.7 Description of problem classes

Cl.[1]	**P**	**V**	**PS**	**α, β and γ**	**Cl.**	**P**	**V**	**PS**	**α, β and γ**	**Cl.**	**P**	**V**	**PS**	**α, β and γ**	**Cl.**	**P**	**V**	**PS**	**α, β and γ**
1	1	1	4	0.025	**19**	1	1	40	0.025	**37**	2	1	4	0.025	**55**	2	1	40	0.025
2	1	1	4	0.05	**20**	1	1	40	0.05	**38**	2	1	4	0.05	**56**	2	1	40	0.05
3	1	1	4	0.1	**21**	1	1	40	0.1	**39**	2	1	4	0.1	**57**	2	1	40	0.1
4	1	2	4	0.025	**22**	1	2	40	0.025	**40**	2	2	4	0.025	**58**	2	2	40	0.025
5	1	2	4	0.05	**23**	1	2	40	0.05	**41**	2	2	4	0.05	**59**	2	2	40	0.05
6	1	2	4	0.1	**24**	1	2	40	0.1	**42**	2	2	4	0.1	**60**	2	2	40	0.1
7	1	3	4	0.025	**25**	1	3	40	0.025	**43**	2	3	4	0.025	**61**	2	3	40	0.025
8	1	3	4	0.05	**26**	1	3	40	0.05	**44**	2	3	4	0.05	**62**	2	3	40	0.05
9	1	3	4	0.1	**27**	1	3	40	0.1	**45**	2	3	4	0.1	**63**	2	3	40	0.1
10	1	1	8	0.025	**28**	1	1	100	0.025	**46**	2	1	8	0.025	**64**	2	1	100	0.025
11	1	1	8	0.05	**29**	1	1	100	0.05	**47**	2	1	8	0.05	**65**	2	1	100	0.05
12	1	1	8	0.1	**30**	1	1	100	0.1	**48**	2	1	8	0.1	**66**	2	1	100	0.1
13	1	2	8	0.025	**31**	1	2	100	0.025	**49**	2	2	8	0.025	**67**	2	2	100	0.025
14	1	2	8	0.05	**32**	1	2	100	0.05	**50**	2	2	8	0.05	**68**	2	2	100	0.05
15	1	2	8	0.1	**33**	1	2	100	0.1	**51**	2	2	8	0.1	**69**	2	2	100	0.1
16	1	3	8	0.025	**34**	1	3	100	0.025	**52**	2	3	8	0.025	**70**	2	3	100	0.025
17	1	3	8	0.05	**35**	1	3	100	0.05	**53**	2	3	8	0.05	**71**	2	3	100	0.05
18	1	3	8	0.1	**36**	1	3	100	0.1	**54**	2	3	8	0.1	**72**	2	3	100	0.1

[1] Class

Figure 6.3 shows the drayage operation time for all classes. The results are divided into eight groups (denoted as a to l) by the P and PS. The P and PS are shown in the upper right-hand corner of each box. Similar to results of Model 2, the results of this set of experiments indicated that the confidence level has an effect on drayage operation time. In particular, the objective function value increases as the level of confidence increases.

The results also suggest that the number of subtasks for (un)packing has an effect on drayage operation time. It can be seen in Figure 6.3 that the drayage operation time decreases as the number of subtasks increases (Version 1 → Version 2 → Version 3). These results correspond to Proposition 6.3 in that the approximation in Proposition 6.2 (MODEL 2) improves if the (un)packing operation can be divided into smaller subtasks. To understand this result, consider a scenario where the unpacking operation is divided into 3 different subtasks (S_i) with different lower and upper bounds (L_i, U_i): $S_1 = [L_1, U_1]$, $S_2 = [L_2, U_2]$ and $S_3 = [L_3, U_3]$. Let A, B and C be the differences between the lower bounds and upper bounds: $A = U_1 - L_1$, $B = U_2 - L_2$ and $C = U_3 - L_3$.

Substituting A, B, and C into the first row of Equation (6.34), we have:

$$\lambda_2^1 = \sqrt{\frac{-\left(A^2 + B^2 + C^2\right) \times \ln \alpha}{2}}$$

Now, suppose that the unpacking operation is divided into only two subtasks: $S_1' = [L_1, U_2]$ and $S_2' = [L_3, U_3]$. In this scenario, the differences between the lower bounds and upper bounds are: $U_2 - L_1 = A + B$ and $U_3 - L_3 = C$.

Substituting $A + B$, and C into the first row of Equation (6.34), we have:

$$\lambda_2^2 = \sqrt{\frac{-\left((A+B)^2 + C^2\right) \times ln\,\alpha}{2}}$$

Lastly, suppose there is only 1 task: $S_1'' = [L_1, U_3]$. In this scenario, the difference between the lower bound and upper bound is: $U_3 - L_1 = A + B + C$.

Substituting $A + B + C$ into the first row of Equation (6.34), we have:

$$\lambda_2^3 = \sqrt{\frac{-(A+B+C)^2 \times ln\,\alpha}{2}}$$

It can be seen above that $\lambda_2^1 < \lambda_2^2 < \lambda_2^3$ because $A^2 + B^2 + C^2 < (A+B)^2 + C^2 < (A+B+C)^2$. The same argument applies to the packing operation. Thus, λ_2 in Equation (6.34) decreases as the number of subtasks increases. The effect of smaller λ_2 is that s_j in Constraints (6.25) and (6.26) is moved to an earlier time. Also, as λ_2 decreases, according to Constraints (6.27) and (6.28), the truck can book an appointment at an earlier time slot. The combination of being able to start job *j* earlier and book an appointment at an earlier time is the reason why drayage operation time decreases as the number of subtasks in (un)packing operation increases

.

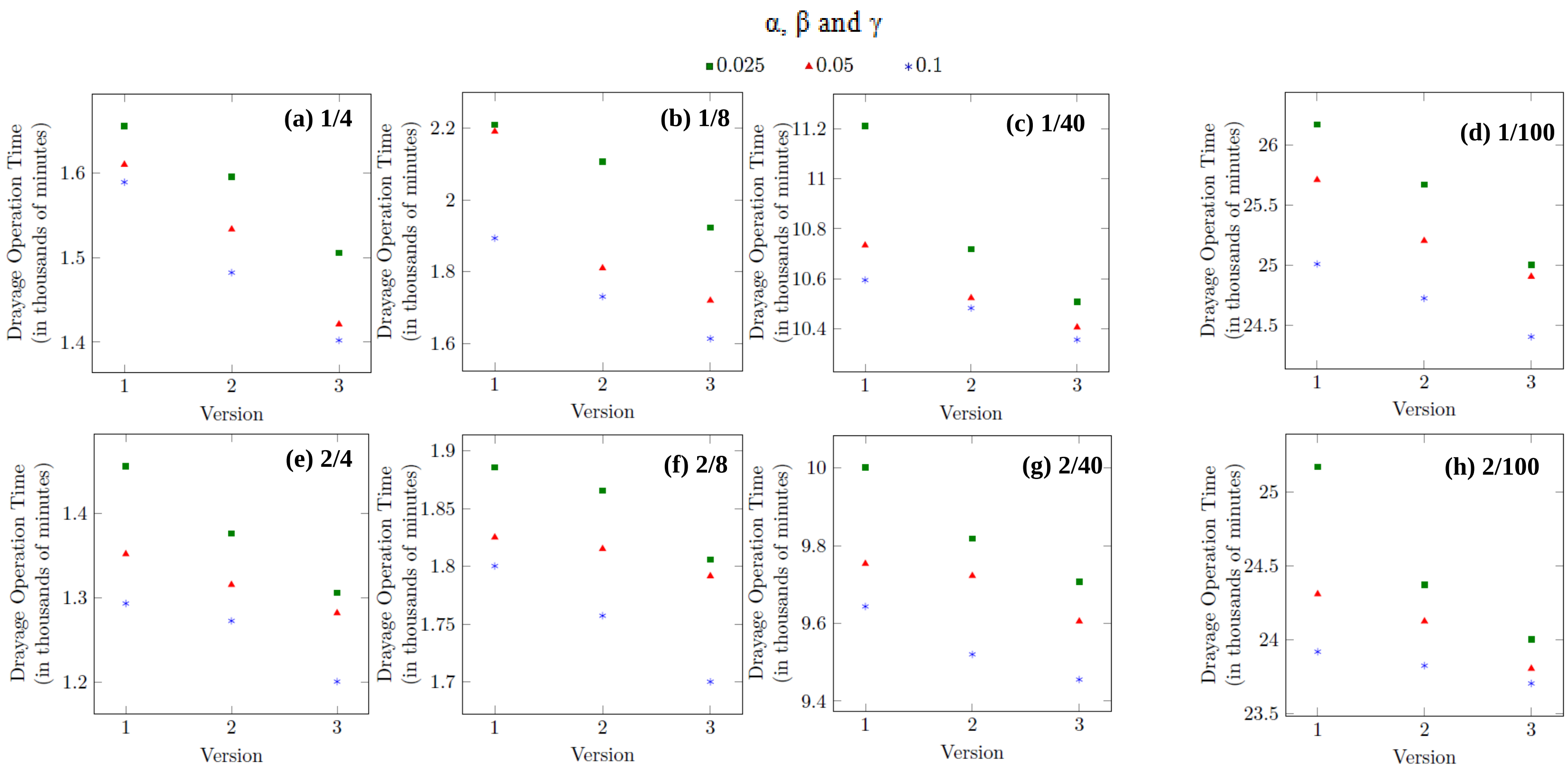


Figure 6.3 Average drayage operation time by the version, according to level of Problem / level of Problem Size

6.4.3 Effects of Considering Uncertainty

As mentioned, in practice (un)packing times are not deterministic which can make the schedule obtained from a deterministic model infeasible. That is, not considering the uncertainty in (un)packing times could lead to being late for an appointment at the container terminal or arriving late at a customer location. There are financial implications for both the drayage firms and shippers/receivers when containers do not arrive on time (e.g., at some container terminals, drayage firms have to pay a fine for missing appointments, receivers such as Walmart could miss out on potential revenue when it does not get its shipment of goods on time). To this end, a series of experiments is conducted to determine how well the schedules produced by the deterministic and stochastic models perform when uncertainty in (un)packing times is considered.

These experiments first involve obtaining the schedules from the deterministic model (Shiri and Huynh, 2016), and the stochastic models (MODEL 1 and MODEL 2 developed in this paper). These schedules are obtained using six different problem sets with the parameter values provided in Table 6 for Version 3 of Problem 1. The problem sets differ by the number of job nodes and customer time windows length, as listed below.

Problem Sets

Set 1. 25 job nodes, 120 minutes
Set 2. 25 job nodes, 150 minutes
Set 3. 25 job nodes, 180 minutes
Set 4. 50 job nodes, 120 minutes
Set 5. 50 job nodes, 150 minutes
Set 6. 50 job nodes, 180 minutes

For each of the above problem sets, two different versions of MODEL 1 and MODEL 2 are used. In version 1, α, β and γ are set to 0.05, and in version 2, α, β and γ are set to 0.1. The combination of models and problem sets yield a total of 30 experiments. Each experiment produces a schedule, and that schedule is evaluated in terms of its feasibility where the (un)packing times are randomly generated within the specified range (see Table 6.8). The process of generating (un)packing times and checking the feasibility of the schedule is repeated for 200 times for each of the 30 experiments. How well each schedule performs in terms of feasibility is shown in Table 6.8.

Table 6.8 Schedule feasibility in percent

(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Problem Set No.	**Deterministic**	**MODEL 1**		**MODEL 2**	
		α, β and γ		**α, β and γ**	
		0.05	**0.1**	**0.05**	**0.1**
1	57.5%	96%	93%	96.5%	93.5%
2	54.5%	96.5%	92.5%	97%	92%
3	59%	96.5%	92.5%	96.5%	92%
4	55%	97%	93.5%	96.5%	92.5%
5	60%	95.5%	92%	95.5%	93%
6	58%	96.5%	91%	96%	92.5%

The first column in Table 6.8 shows the problem set number. The second column shows the percentage of feasibility for the deterministic model. The third and fourth columns show the percentage of feasibility for MODEL 1. Lastly, the fifth and sixth columns show the percentage of feasibility for MODEL 2. The results indicate that the deterministic model has a lower percentage of feasibility compared to the stochastic models. As expected, the reason is that deterministic model did not account for uncertainty in (un)packing times. For the stochastic models (MODELs 1 and 2), as the user-specified confidence level increases the percentage of feasibility also increases. In terms of customer time windows length, the results from problem sets 1, 2, and 3 and also problem sets 4, 5 and 6 (with length increases from 120 to 180 minutes) indicate that there is no correlation between the length of the time window and the percentage of feasibility.

The experimental results indicate that in order to make reliable logistics decisions, drayage firms need to consider the uncertainty in processing times of various drayage operations. As illustrated, not considering uncertainty in (un)packing times could cause a truck to miss its appointment at the terminal or time window at the customer location, and in the long run lower its service level. The developed models provide drayage firms with the ability to design a robust schedule that would accommodate uncertainty at the desired confidence level; for example, drayage firms could design a schedule that would be feasible 95% of the time. This capability is crucial for drayage firms that wish to guarantee a certain level of service to their customers. That is, drayage firms could make guarantees to their customers that they will be able to make the delivery on time, for example, 99% of the time. Obviously, there is a tradeoff in cost; the higher the percentage of on-time delivery the higher the cost, as illustrated in Figures 6.2 and 6.3 (in terms of drayage operation time).

6.5 SUMMARY AND CONCLUSION

This paper developed two models to relax the assumption of deterministic container (un)packing times. These models can be used when an accurate probability distribution for (un)packing are not available. MODEL 1 requires the mean and variance of the (un)packing times to be known while MODEL 2 requires that the mean and the lower and upper bounds of the (un)packing times are known. A set of experiments was conducted, and the results indicated that 1) the planned drayage operation time increases as mean and variance of the (un)packing time increases, 2) the planned drayage operation time decreases as the number of subtasks in container (un)packing operation increases, 3) the planned drayage operation time increases as the user-specified level of confidence increases, 4) the deterministic model has a lower percentage of feasibility compared to the developed stochastic models, and 5) percentage of feasibility increases as user-specified confidence level increases.

This study has a few limitations that should be taken into account: 1) only (un)packing times in drayage operation are assumed to be uncertain, but in practice, the duration of all other processes such as truck turn time is uncertain, 2) it is assumed that demands are known *a priori*, but in practice, there are situations where some jobs are added and/or some jobs are removed from a truck's schedule, and 3) it is assumed that trucks will follow the prescribed routes, but in practice, there are situations when trucks will need to make detours or take alternate routes.

ACKNOWLEDGMENT

This paper is based upon work supported by the National Science Foundation under Grant no. 1100227.

This is an Accepted Manuscript of an article published by Taylor & Francis in Journal of Journal of the Operational Research Society on 3/16/2018, available online: http://wwww.tandfonline.com/10.1080/01605682.2018.1457487.

CHAPTER 7: REAL-TIME SCHEDULING OF DRAYAGE PROBLEM

(FUTURE WORK)

7.1 INTRODUCTION

Drayage operation occurs in a dynamic environment which means part or all of the data is dynamically revealed and evolved during the operation. This data includes customer location, shipper and receiver information, loading and unloading information, travel time, terminal turn time and the position of the vehicles. When drayage problem is treated as a static and deterministic problem, any unexpected incident such as traffic congestion, accidents and road closures (i.e., Gassman et al., 2017 and Sasanakul et al., 2017) that occur during operation could cause delays. In addition, in practice, there are situations when jobs are canceled and new ones are added on the fly. Recent advancements in communication and information technologies provided the opportunity to manage drayage trucks in real-time.

In this work, the real-time scheduling of drayage problem is considered. It would assume trucks' locations, travel times, and customer requests are updated throughout the day. An approach based on re-optimization of the drayage problem will be developed which consist of two phases (shown in Figure 7.1): (1) initial optimization, and (2) re-optimization. The initial optimization involves creating an initial schedule covering known requests at the beginning of the day using current travel times and service times (Phase I shown in Figure 7.1). During operation as the day progresses, the re-optimization phase will be triggered (Phase II shown in Figure 7.1): 1) every predefined period of time, and 2) with an unexpected change in travel time, service time and requests. When re-optimization is triggered, a snapshot of the state of all tasks and the position all trucks are taken, and then input data are updated.

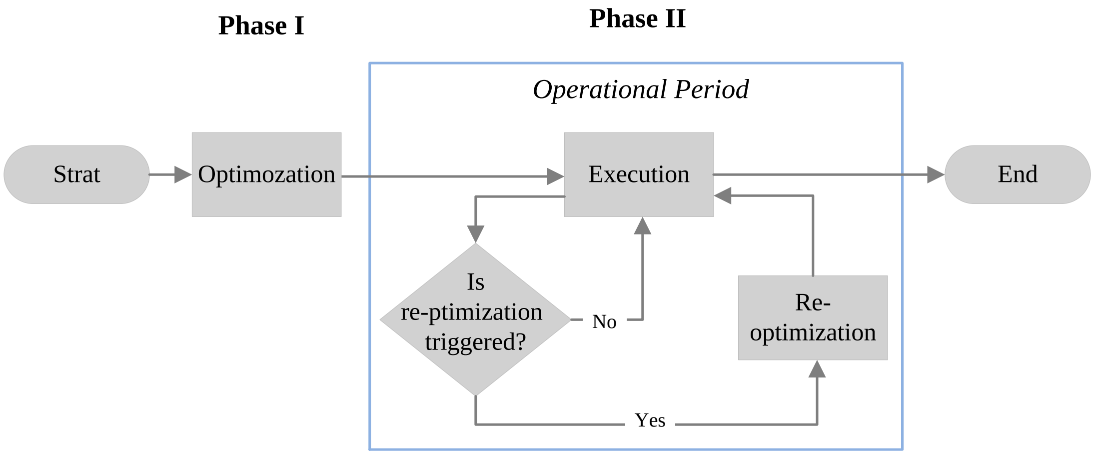


Figure 7.1 Flowchart of two-phase re-optimization approach

As future work, we would take the following steps:

Step 1) Develop a model for real-time scheduling of drayage problem.

Step 2) Develop solution methods to tackle the problem in a reasonable time.

Step 3) To demonstrate the feasibility of the developed models, they are tested on problem instances with real-life characteristics.

CHAPTER 8: CONCLUSION

In this dissertation, four completed studies are presented that addressed real-world problem in drayage operation. This dissertation contributes to the drayage literature and incorporates real-world features into developed models to reduce the gap between real-world drayage planning and mathematical modeling. Also, as the efficient solutions to the considered problems contribute to drayage productivity, this dissertation developed solution methodologies based on RTS that provide optimal solutions for the small-sized problem and can solve realistic-sized problems efficiently.

Chapter 3 of this dissertation addressed a new challenge posed to drayage companies by appointment system that requires trucks to make appointments in advance. It makes dispatcher's job further complicated by the fact that customers operate in certain time windows and that the container terminal requires trucks to make appointments in advance. A mixed-integer quadratic programming model is proposed that solve the empty container allocation problem, vehicle routing problem, and appointment booking problem in an integrated manner. A RTS algorithm combined with a greedy algorithm is developed to tackle the problem. The experimental results show that developed integrated model is feasible. Also, the results indicate that RTS can find the optimal solutions for small-sized problems and can solve operational problems within reasonable time. The developed model and algorithm are used to evaluate the effect of the truck appointment system on the efficiency of drayage operation.

Chassis is one of the transportation resource that should be provided in drayage operation. Chapter 4 presents the work that reduces the gap between real-world drayage problem and mathematical modeling by incorporating chassis allocation problem into the drayage scheduling model. The developed mixed-integer programming model simultaneously solves scheduling of tractors, full containers, empty containers, and chassis. Also, it extends the drayage literature by incorporating these features into drayage problem: (1) ensuring that container and chassis are of the same size and type, (2) considering the possibility that drayage companies can sub-contract the work to owner-operators, and (3) a heterogeneous mix of drayage vehicles (from company fleet and owner-operators) with different start and end locations is considered; drayage company's trucks start at company's depot and should return to one of the company's depots whereas owner-operators' trucks should return to the same location from where they originated. To efficiently solve the developed model, RTS combined with an insertion heuristic is developed. The model and algorithm are used to evaluate the effectiveness of different chassis supply models in the U.S.

Chapter 5 of this dissertation studies the impact a new trend in the North American terminal in establishment of auxiliary or satellite facilities to store, stage, or transfer loaded containers, empty containers, and container chassis outside container terminal on drayage operation. This work extends our previous work to incorporate second-tier facilities into the mathematical model and considered a drop yard (i.e., second-tier facility) for picking up or/and dropping off loaded containers outside the marine container terminal. Also, it incorporates the following features into our previous mathematical model: (1) trucks do not have to wait at customers' locations during the packing and unpacking operations, and

(2) the job requests by customers is extended to include empty container pickup, loaded container pickup, empty container delivery, and loaded container delivery. To solve the problem a RTS developed by the authors is used.

In aforementioned works in Chapters 3 to 5, a deterministic version of drayage problem is considered, and hence, they did not account for uncertainty in drayage operation. Chapter 6 extends our previous work by considering a stochastic version of drayage problem. It assumes uncertainty in the (un)packing times. Two chance-constrained programming models were developed for situations which: 1) the mean and variance of the (un)packing times are available, and 2) the mean as well as the upper and lower bounds of the (un)packing times are available. These models were converted to their deterministic equivalent to keep them tractable using Cantelli's and Hoeffding's inequalities. To solve these models, the commercial solver CPLEX was used for small-sized problems. A RTS combined with an insertion heuristic (developed by the authors) was used for medium and large-sized problems.

Chapter 7 represents the extensions to be covered in the future work. The aforementioned works in Chapters 3 to 6 does not consider cases where trucks need to be rerouted due to accidents or road closures. The developed integrated models can be further enhanced to represent reality by considering the real-time scheduling of drayage problem. It would assume trucks' locations, travel times, and customer requests are updated throughout the day. An approach based on the re-optimization of the drayage problem would be developed which consist of two phases as follows: (1) initial optimization at the beginning of the day, and (2) re-optimization during operation.

REFERENCES

[1] Antony, J., 2014. Design of experiments for engineers and scientists. Elsevier.

[2] APGST Summary Report, 2013. Available: Understanding container drayage owner-operators in metro Vancouver. http://apgst.ca/projects/pdfs/drayageowner-operatorsreport2013.pdf [Accessed 10 October 2016]

[3] Battiti, R., Tecchiolli, G., 1994. The reactive tabu search. ORSA Journal on Computing 6 (2), 126- 140.

[4] Bensman, D., Bromberg, Y., 2009. Report on port truckers survey at New Jersey ports.

[5] Berbeglia, G., Cordeau, J.F., Gribkovskaia, I. and Laporte, G., 2007. Static pickup and delivery problems: a classification scheme and survey. Top, 15(1), pp.1-31.

[6] Birge, J.R. and Louveaux, F., 2011. Introduction to stochastic programming. Springer Science & Business Media.

[7] Bonney, J. and Mongelluzzo, B., 2014. Three largest US ports seek ways to resolve chassis crisis. Journal of Commerce. URL: http://www.joc.com/trucking-logistics/drayage/three-largestus-ports-seek-ways-resolve-chassis-crisis_20140721.html.

[8] Boucheron, S., Lugosi, G. and Massart, P., 2013. Concentration inequalities: A nonasymptotic theory of independence. Oxford university press. Hoeffding, W., 2012. The collected works of Wassily Hoeffding. Springer Science & Business Media.

[9] Braekers, K., Caris, A., Janssens, G.K., 2013. Integrated planning of loaded and empty container movements. OR Spectrum, 35(2), 457-478.

[10] Braekers, K., Caris, A., Janssens, G.K., 2014. Bi-objective optimization of drayage operations in the service area of intermodal terminals. Transportation Research Part E 65, 50-69.

[11] Braekers, K., Janssens, G. K., Caris, A., 2011. Challenges in managing empty container movements at multiple planning levels. Transport Reviews 31(6), 681-708.

[12] Caris, A., Janssens, G. K., 2009. A local search heuristic for the pre-and end-haulage of intermodal container terminals. Computers and Operations Research 36, 2763-2772.

[13] Chang, H., Jula, H., Chassiakos, A. and Ioannou, P., 2008. A heuristic solution for the empty container substitution problem. *Transportation Research Part E: Logistics and Transportation Review*, *44*(2), pp.203-216.

[14] Cheetah chassis. http://www.cheetahchassis.com/containerchassis/40-45-48-53-extendable-60-spread-3-axle-chassis/

[15] Chen, G., Govindan, K., Yang, Z. Z., Choi, T. M., Jiang, L., 2013. Terminal appointment system design by non-stationary M(t)/Ek/c(t) queueing model and genetic algorithm. Int. J. Production Economics 146 , 694-703.

[16] Chen, G., Yang, Z., 2010. Optimizing time windows for managing export container arrivals at Chinese container terminals. Maritime Economics and Logistics, 12(1), 111-126.

[17] Chen, G., Yang, Z., Jiang, L., 2010. Reducing marine container terminal gate congestion with vessel-dependent time windows for truck entries. Transportation Research Board 89th Annual Meeting (No. 10-0545).

[18] Chen, K., 2015. Performance Evaluation by Simulation and Analysis with Applications to Computer Networks. John Wiley & Sons.

[19] Cheung, R. K., Hange, D. D., 2003. A time-window sliding procedure for driver-task assignment with random service times. IIE Transactions 35, 433-444.

[20] Cheung, R.K., Hang, D.D. and Shi, N., 2005. A labeling method for dynamic driver-task assignment with uncertain task durations. Operations Research Letters, 33(4), pp.411-420.

[21] Chiang, W. C., Russell, R. A., 1997. A reactive tabu search metaheuristic for the vehicle routing problem with time windows. INFORMS Journal on Computing 9 (4), 417-430.

[22] Chung, K. H., Ko, C. S., Shin, J. Y., Hwang, H., Kim, K. H., 2007. Development of mathematical models for the container road transportation in Korean trucking industries. Computers and Industrial Engineering 53, 252-262.

[23] Cordeau, J.F., Laporte, G., Mercier, A., 2001. A unified tabu search heuristic for vehicle routing problems with time windows. J. Operation Research Soc. 52, 928–936.

[24] Crainic, T. G., Gendreau, M., Dejax, P., 1993. Dynamic and stochastic models for the allocation of empty Dynamic and stochastic models for the allocation of empty. Operation Research 41 (1), 102-126.

[25] Crainic, T.G. and Kim, K.H., 2007. Intermodal transportation. Handbooks in operations research and management science, 14, pp.467-537.

[26] Demir, E., Bektaş, T. and Laporte, G., 2011. A comparative analysis of several vehicle emission models for road freight transportation. Transportation Research Part D: Transport and Environment, 16(5), 347-357.

[27] Dotoli, M. and Epicoco, N., 2016, October. A technique for the optimal management of containers' drayage at intermodal terminals. In *Systems, Man, and Cybernetics (SMC), 2016 IEEE International Conference on* (pp. 000566-000571). IEEE.

[28] Dotoli, M., Epicoco, N., Falagario, M., Seatzu, C. and Turchiano, B., 2017. A decision support system for optimizing operations at intermodal railroad terminals. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, *47*(3), pp.487-501.

[29] Escudero-Santana, A., Cortés, P., MuÁąuzuri, J. and Aparicio, P., 2015. A viral system to optimise the daily drayage problem. *International Journal of Bio-Inspired Computation*, *7*(3), pp.176-182.

[30] Escudero, A., Muñuzuri, J., Arango, C., Onieva, L., 2011. A satellite navigation system to improve the management of intermodal drayage. Advanced Engineering Informatics 25, 427-434.

[31] Escudero, A., Muñuzuri, J., Guadix, J., Arango, C., 2013. Dynamic approach to solve the daily drayage problem with transit time uncertainty. Computers in Industry 64, 165-175.

[32] FHWA-PL-98-034: U.S. Department of Transportation, Federal Highway Administration. (1998) U.S. Freight Economy in Motion.

[33] Fourer, R., Gay, D. M. Gay and Kernighan, B. W., 2003, AMPL—a modeling language for mathematical programming. https://orfe.princeton.edu/~rvdb/307/textbook/AMPLbook.pdf [Accessed 10 September 2017]

[34] Fremantle Ports. (Retrieved August 28, 2017, from http://www.fremantleports.com.au/Operations/Landside/Pages/Supply-chain-overview.aspx)

[35] Funke, J. and Kopfer, H., 2016. A model for a multi-size inland container transportation problem. Transportation Research Part E: Logistics and Transportation Review, 89, 70-85.

[36] Gassman, Sarah L., Inthuorn Sasanakul, Charles E. Pierce, Emad Gheibi, Ryan Starcher, William Ovalle, and Mostaqur Rahman. "Failures of Pipe Culverts from

a 1000-Year Rainfall Event in South Carolina." In Geotechnical Frontiers 2017, pp. 114-124.

[37] (GCCG) Gateway Cities Council of Governments. http://www.polb.com/civica/filebank/blobdload.asp?BlobID=3724

[38] Glover, F., 1986. Future paths for integer programming and links to artificial-intelligence. Computer Operation Research 13, 533–549.

[39] Hartman, B.C. and Clott, C., 2015. Intermodal chassis supply in the US-A Bayesian game model. Research in Transportation Business & Management, 14, 66-71.

[40] Hickman, J., Hassel, D., Joumard, R., Samaras, Z., Sorenson, S., 1999. MEET-Methodology for Calculating Transport Emissions and Energy Consumption. European Commission, DG VII. Technical Report. http://www.transport-research.info/Upload/Documents/200310/meet.pdf

[41] Hoeffding, W. (1963). Probability inequalities for sums of bounded random variables. Journal of the American statistical association, 58(301), 13-30.

[42] Huynh, N., Smith, D., Harder, F., 2016. Truck appointment systems: where we are and where to go from here. Transportation Research Board 95th Annual Meeting (No. 16-5663)

[43] Ileri, Y., 2006. Drayage optimization in truck/rail networks (Doctoral dissertation, Georgia Institute of Technology).

[44] Ileri, Y., Bazaraa, M., Gifford, T., Nemhauser, G., Sokol, J., Wikum, E., 2006. An optimization approach for planning daily drayage operations. CEJOR 14, 141–156.

[45] ILIADIS TRANSPORTS SA. (Retrieved August 28, 2017, http://www.eliadis.gr/en/ipiresies/transport/item/11-metafores-containers.html)

[46] Imai, A., Nishimura, E., Current, J., 2007. A Lagrangian relaxation-based heuristic for the vehicle routing with full container load. European Journal of Operational Research 176, 87-105.

[47] Intercon Modular. http://www.inter-con.us/pages/standardunits.htm

[48] Jaffee, D., Rowley, A., 2009. Hauling containers: port drayage drivers in the logistics supply chain. Available at SSRN 1617348.

[49] Jeter, M., 1986. Mathematical programming: an introduction to optimization(Vol. 102). CRC press.

[50] Jula, H., Dessouky, M., Ioannou, P., Chassiakos, A., 2005. Container movement by trucks in metropolitan networks: modeling and optimization. Transportation Research Part E 41, 235-259.

[51] Kim, N.S. and Van Wee, B., 2014. Toward a better methodology for assessing CO2 emissions for intermodal and truck-only freight systems: A European case study. International Journal of Sustainable Transportation, 8(3), pp.177-201.

[52] Lai, M., Crainic, T.G., Di Francesco, M. and Zuddas, P., 2013. An heuristic search for the routing of heterogeneous trucks with single and double container loads. Transportation Research Part E: Logistics and Transportation Review, 56, 108-118.

[53] Liu, B. and Iwamura, K., 1998. Chance constrained programming with fuzzy parameters. Fuzzy sets and systems, 94(2), pp.227-237.

[54] Logistics Executive. (Retrieved August 28, 2017, from http://www.logisticsexecutive.com/category/ceo-newsletters/

[55] Macharis, C. and Bontekoning, Y.M., 2004. Opportunities for OR in intermodal freight transport research: A review. European Journal of operational research, 153(2), pp.400-416.

[56] Mahmoudi, M., Chen, J. and Zhou, X., 2016. Embedding Assignment Routing Constraints through Multi Dimensional Network Construction for Solving the Multi Vehicle Routing Problem with Pickup and Delivery with Time Windows. arXiv preprint arXiv:1607.01728.

[57] Mahmoudi, M. and Zhou, X., 2016. Finding optimal solutions for vehicle routing problem with pickup and delivery services with time windows: A dynamic programming approach based on state–space–time network representations. Transportation Research Part B: Methodological, 89, pp.19-42.

[58] Máhr, T., Srour, J., Weerdt, M. d., Zuidwijk, R., 2010. Can agents measure up? A comparative study of an agent-based and on-line optimization approach for a drayage problem with uncertainty. Transportation Research Part C 18, 99-119.

[59] (MARAD) U.S. Department of Transportation, Maritime Administration https://www.marad.dot.gov/resources/data-statistics/#Historic Fleet Reports [Accessed 10 September 2017]

[60] Marković, N., Drobnjak, Ž. and Schonfeld, P., 2014. Dispatching trucks for drayage operations. Transportation Research Part E: Logistics and Transportation Review, 70, 99-111.

[61] Montgomery, D.C., 2008. Design and analysis of experiments. John Wiley & Sons.

[62] Morlok, E. K., Spasovic, L. N., 1994. Approaches for improving drayage in rail-truck intermodal service. https://transportation.njit.edu/NCTIP/final_report/approaches_for_ improving_ drayage.htm.

[63] Namboothiri, R., Erera, A. L., 2008. Planning local container drayage operations given a port access appointment system. Transportation Research Part E 44, 185-202.

[64] NCFRP Report 11, 2011. Truck Drayage productivity guide. Transportation Research Board of the National Academies, Washington, D.C.

[65] NCFRP Report 20, 2012. Guidebook for Assessing Evolving International Container Chassis Supply Models. Transportation Research Board of the National Academies, Washington, D.C.

[66] Nossack, J. and Pesch, E., 2013. A truck scheduling problem arising in intermodal container transportation. European Journal of Operational Research, 230(3), 666-680.

[67] Osman, I. H., 1993. Metastrategy simulated annealing and tabu search algorithms for the vehicle routing problem. Annals of Operations Research 41, 421-451.

[68] Osman, I. H., Wassan, N. A., 2002. A reactive tabu search meta-heuristic for the vehicle routing problem with back-hauls. Journal of Scheduling, 5(4), 263-285.

[69] Peoples, J., Talley, W.K., 2004. Owner-Operator truck driver earnings and employment: port cities and deregulation. Research in Transportation Economics 10, 191-213.

[70] Popović, D., Vidović, M., Nikolić, M., 2014. The variable neighborhood search heuristic for the containers drayage problem with time windows. Soft Computing in Industrial Applications 223, 351-364.

[71] Rezaeifar, F., Najafi, M., Ardekani, S.A. and Shahooei, S., 2017, Optimized Terminal Design for UFT Systems in Integrated Subterranean Pipeline Infrastructure. In Pipelines, 528-539.

[72] Rao, S.S. and Rao, S.S., 2009. Engineering optimization: theory and practice. John Wiley & Sons.

[73] Rodrigue, J.P., Zumerchik, J., Ogard, E.L., 2012. The US transition to a motor carrier supplied marine chassis: operational impacts on and off terminal.

[74] Ryder. https://reservations.ryder.com/en/view-all-vehicles.

[75] Savelsbergh, M.W. and Sol, M., 1995. The general pickup and delivery problem. Transportation science, 29(1), pp.17-29.

[76] Sasanakul, Inthuorn, Sarah L. Gassman, Charles E. Pierce, William Ovalle, Ryan Starcher, Emad Gheibi, and Mostaqur Rahman. "Dam Failures from a 1000-Year Rainfall Event in South Carolina." In Geotechnical Frontiers 2017, pp. 244-254. 2017. DOI: 10.1061/9780784480458.024

[77] Shiri, S. and Huynh, N., 2015. An Agent-Based Approach to Solve the Daily Drayage Problem, 19th Annual Meeting on Agent-Based Modeling & Simulation.

[78] Shiri, S. and Huynh, N., 2015. Planning of Container Movement by Trucks in Metropolitan Area, INFORMS Annual Meeting annual meeting.

[79] Shiri, S. and Huynh, N., 2016. Drayage Scheduling with Time Window Constraints at Customer Locations and Marine Container Terminal. Transportation Research Board 95th Annual Meeting.

[80] Shiri, S. and Huynh, N., 2016. Optimization of drayage operations with time-window constraints. International Journal of Production Economics, 176, pp.7-20.

[81] Shiri, S. and Huynh, N., 2016, The Impact of U.S. Chassis Supply Models on Drayage Productivity, INFORMS Annual Meeting.

[82] Shiri, S. and Huynh, N., 2017. The Implications of U.S. Chassis Supply Models for Chassis Stakeholders, Transportation Research Board 96th Annual Meeting of the Transportation Research Board.

[83] Shiri, S. and Huynh, N., 2017, Impact of Free-flow Operation on Drayage Productivity, INFORMS Annual Meeting.

[84] Shiri, S. and Huynh, N., 2017. Assessment of US chassis supply models on drayage productivity and air emissions. Transportation Research Part D: Transport and Environment.

[85] Shiri, S., Ng, N, Huynh, N., Integrated Drayage Scheduling Problem with Stochastic Container Packing and Unpacking Times. Accepted to be published in Journal of the Operational Research Society. DOI: 10.1080/01605682.2018.1457487.

[86] Shiri, S., Smith, D., N, Huynh, N., Harder, F., Impact of second-tier container port facilities on drayage operation. Submitted in Transportation Research Part E.

[87] Shiri, S., Smith, D., Huynh, N., and Harder, F., 2018, Emergence and Impacts of Second-Tier Container Port Facilities, Proceeding of 97th Annual Meeting of the Transportation Research Board.

[88] Shiri, S., Ng, M., Huynh, N., 2018. Distribution-Free Scheduling of Drayage Operation under Uncertainty, Proceeding of 97th Annual Meeting of the Transportation Research Board.

[89] Smilowitz, K., 2006. Multi-resource routing with flexible tasks: an application in drayage operations. IIE Transactions 38, 555-568.

[90] Smith, D., Harder, F., Huynh, N., Hutson, N., Harrison, R., 2012. Analysis of current and emerging drayage practices. Transportation Research Record: Journal of the Transportation Research Board 2273, 69-78.

[91] Solomon, M.M., 1987. Algorithms for the vehicle-routing and scheduling problems with time window constraints. Operation Research, 35(2), 254–265.

[92] Song, Y., Zhang, J., Liang, Z. and Ye, C., 2017. An exact algorithm for the container drayage problem under a separation mode. Transportation Research Part E: Logistics and Transportation Review, 106, pp.231-254.

[93] Sterzik, S. and Kopfer, H., 2013. A tabu search heuristic for the inland container transportation problem. Computers & Operations Research, 40(4), 953-962.

[94] Sterzik, S., Kopfer, H., Yun, W. Y., 2015. Reducing hinterland transportation costs through container sharing. Flexible Services and Manufacturing Journal 27, 382-402.

[95] U.S. Census Bureau, Available: https://www.census.gov/foreign-trade/balance/c0004.html [Accessed 10 October 2016].

[96] Vidović, M., Nikolić, M. and Popović, D., 2012. Two mathematical formulations for the containers drayage problem with time windows. 2nd International Conference on Supply Chains ICSC.

[97] Vidović, M., Popović, D., Ratković, B. and Radivojević, G., 2016. Generalized mixed integer and VNS heuristic approach to solving the multisize containers drayage problem. International Transactions in Operational Research.

[98] Vidović, M., Radivojević, G. and Raković, B., 2011. Vehicle routing in containers pickup up and delivery processes. Procedia-Social and Behavioral Sciences, 20, 335-343.

[99] Wallace, S.W. and Ziemba, W.T. eds., 2005. Applications of stochastic programming. Society for Industrial and Applied Mathematics.

[100] Wang, X., Kopfer, H., 2015. Rolling horizon planning for a dynamic collaborative routing problem with full-truckload pickup and delivery requests. Flexible Services and Manufacturing Journal, 1-25.

[101] Wang, X., Regan, A. C., 2002. Local truckload pickup and delivery with hard time window constraints. Transportation Research Part B 36, 97-112.

[102] Wassan, N. A., Wassan, A. H., Nagy, G., 2008. A reactive tabu search algorithm for the vehicle routing problem with simultaneous pickups and deliveries. Journal of Combinatorial Optimization 15, 368-386.

[103] Williams, H.P., 1990. Model building in mathematical programming. Wiley.

[104] Williams, H.P., 2013. Model building in mathematical programming. John Wiley & Sons.

[105] Woodruff, D. L., Zemel, E., 1993. Hashing vectors for tabu search. Annals of Operations Research 41, 123-137.

[106] Xue, Z., Zhang, C., Lin, W. H, Miao, L., Yang, P., 2014. A tabu search heuristic for the local container drayage problem under a new operation mode. Transportation Research Part E 62, 136-150.

[107] Zhang, H., Zhang, R., Huang, M. and Shi, H., 2015, May. Modeling and analyses of container drayage transportation problem with the objective of low carbons. In Control and Decision Conference (CCDC), 2015 27th Chinese (pp. 4654-4658). IEEE.

[108] Xue, Z., Zhang, C., Yang, P. and Miao, L., 2015. A combinatorial Benders' cuts algorithm for the local container drayage problem. Mathematical Problems in Engineering.

[109] Zetes Corporate (Retrieved August 28, 2017, from http://www.zetes.com/supply-chain/news/zetes-collaborative-supply-chain-suite-six-solutions-drive-process-optimisation)

[110] Zhang, G., Smilowitz, K., Erera, A., 2011. Dynamic planning for urban drayage operations. Transportation Research Part E 47, 764-777.

[111] Zhang, R., Yun, W. Y., Kopfer, H., 2010. Heuristic-based truck scheduling for inland container transportation. OR Spectrum 32, 787-808.

[112] Zhang, R., Yun, W. Y., Kopfer, H., 2015. Multi-size container transportation by truck: modeling and optimization. Flexible Services and Manufacturing Journal 27 , 403-430.

[113] Zhang, R., Yun, W. Y., Moon, I., 2009. A reactive tabu search algorithm for the multi-depot container truck transportation problem. Transportation Research Part E 45, 904-914.

[114] Zhang, R., Lu, J.C. and Wang, D., 2014. Container drayage problem with flexible orders and its near real-time solution strategies. Transportation Research Part E: Logistics and Transportation Review 61, 235-251.

APPENDIX A: COPYRIGHT PERMISSIONS TO REPRINT

A.1 CHAPTER 3 COPYRIGHT PERMISSION

Copyright Clearance Center | RightsLink®

Home | Account Info | Help

Title: Optimization of drayage operations with time-window constraints

Author: Samaneh Shiri,Nathan Huynh

Publication: International Journal of Production Economics

Publisher: Elsevier

Date: June 2016

Logged in as:
Samaneh Shiri
Account #:
3001251931

LOGOUT

Please note that, as the author of this Elsevier article, you retain the right to include it in a thesis or dissertation, provided it is not published commercially. Permission is not required, but please ensure that you reference the journal as the original source. For more information on this and on your other retained rights, please visit: https://www.elsevier.com/about/our-business/policies/copyright#Author-rights

BACK | CLOSE WINDOW

A.2 CHAPTER 4 COPYRIGHT PERMISSION

Copyright Clearance Center RightsLink®

Home | Account Info | Help

Title: Assessment of U.S. chassis supply models on drayage productivity and air emissions
Author: Samaneh Shiri,Nathan Huynh
Publication: Transportation Research Part D: Transport and Environment
Publisher: Elsevier
Date: Available online 4 May 2017

Logged in as:
Samaneh Shiri
Account #:
3001251931
LOGOUT

Please note that, as the author of this Elsevier article, you retain the right to include it in a thesis or dissertation, provided it is not published commercially. Permission is not required, but please ensure that you reference the journal as the original source. For more information on this and on your other retained rights, please visit: https://www.elsevier.com/about/our-business/policies/copyright#Author-rights

BACK | CLOSE WINDOW

A.3 CHAPTER 6 COPYRIGHT PERMISSION

3/28/2018 Gmail - Permission to use the paper in the dissertation [ref:_00D0Y35lji._5000YT65aA:ref]

Gmail **Samaneh Shiri <samashiri@gmail.com>**

Permission to use the paper in the dissertation [ref:_00D0Y35lji._5000YT65aA:ref]

---

authorqueries@tandf.co.uk <authorqueries@tandf.co.uk> Wed, Mar 28, 2018 at 6:58 AM
To: "samashiri@gmail.com" <samashiri@gmail.com>

Taylor & Francis Group
an informa business

Thank you for your email.

As the author of the original article, you have the right to include the article in a thesis or dissertation that is not to be published commercially, provided that acknowledgement in the journal is noted.

This is an Accepted Manuscript of an article published by Taylor & Francis in *Journal of XXX* on *DATE*, available online: *http://wwww.tandfonline.com/DOI*

Please see this guide for further information: http://authorservices.taylorandfrancis.com/sharing-your-work/

Best wishes

Sherry Howard
On behalf of Author Services