Computers & Operations Research 41 (2014) 412–422

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

Robust berth scheduling at marine container terminals via hierarchical optimization

Mihalis Golias [a,*], Isabel Portal [b], Dinçer Konur [c], Evangelos Kaisar [d], Georgios Kolomvos [e]

[a] Department of Civil Engineering and Intermodal Freight Transportation Institute, University of Memphis, United States
[b] Department of Ocean and Mechanical Engineering, Florida Atlantic University, United States
[c] Department of Engineering Management and Systems Engineering, Missouri University of Science and Technology, United States
[d] Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University, United States
[e] Industrial Engineering and Optimization Laboratory, Kathikas Institute of Research and Technology, Cyprus

ARTICLE INFO

Available online 9 August 2013

Keywords:
Berth scheduling
Container terminals
Bi-level
Bi-objective
Metaheuristics

ABSTRACT

In this paper, we present a mathematical model and a solution approach for the discrete berth scheduling problem, where vessel arrival and handling times are not known with certainty. The proposed model provides a robust berth schedule by minimizing the average and the range of the total service times required for serving all vessels at a marine container terminal. Particularly, a bi-objective optimization problem is formulated such that each of the two objective functions contains another optimization problem in its definition. A heuristic algorithm is proposed to solve the resulting robust berth scheduling problem. Simulation is utilized to evaluate the proposed berth scheduling policy as well as to compare it to three vessel service policies usually adopted in practice for scheduling under uncertainty.

1. Introduction

Marine container terminals are essential components of global supply chains and terminal operators face many challenges on day to day operations to remain efficient and competitive. Most of these challenges are due to the interactions between different operations and facilities within the terminals. For instance, berth scheduling with respect to vessel characteristics considering the storage, loading, and unloading operations at the yard side is a daily challenge for terminal operators. Another challenge comes from assigning vessels to the available berths depending on different service policies followed by the terminal operator [1,2]. Terminal operators should overcome these challenges to improve their performance measures and stay competitive. Specifically, there is a growing industry interest to expand the metrics in reliability and understand the gap in container delivery and liner schedule reliability.[1] It is, therefore, crucial to evaluate the causes and the effects of shipment delays.

To stay competitive, terminal operators should develop accurate and reliable berth schedules in order to avoid its customers' shipment delays. Berth scheduling refers to the allocation of a specific vessel to a particular physical location within the port for loading/unloading processes. This paper concentrates in the development of a berth schedule that explicitly accounts for the uncertainties in vessel arrivals and handling times. Even though port operators may have an estimated vessel arrival time window, it is difficult to know the exact arrival time in advance (e.g., delay due to weather, delay at port of origin). In addition, due to a number of operational factors (e.g., quay crane breakdowns, yard congestion, changes to stowage plan, etc.) terminal operators can usually only estimate an upper and a lower bound on the vessels' handling times.

A significant amount of research has been conducted to analyze and improve berth scheduling policies (we refer to [2] for an excellent and recent literature review and classification on seaside operations at marine container terminals). The research studies on berth scheduling could be classified considering four main assumptions on the inherent characteristics of the problem [1,2]. The first assumption is on the definition of the berth space as discrete or continuous space. In case of discrete space, the wharf is divided into a specific number of berths. On the other hand, continuous space defines the entire wharf as the berth space. We note that a third case exist (hybrid) where the wharf is discretized in berths but multiple vessels can be served at each berth simultaneously [2]. The second assumption is on the dynamic or static nature of vessel arrivals. Particularly, while static vessel arrivals refer to the case where all vessels are at the port when the schedule is developed, the dynamic vessel arrivals formulation assumes that arrival times are known within a time window. The third assumption refers to deterministic versus stochastic nature of handling times. While handling times are assumed to be known in deterministic handling time formulations, handling times are assumed to

* Corresponding author. Tel.: +1 901 678 3048; fax: +1 901 678 3026.
E-mail addresses: mihalisdgolias@gmail.com, mgkolias@memphis.edu (M. Golias).

[1] American Shipper: New report compares liner, container delivery reliability. [Internet]. [Cited: 20 July 2012]. Available from http://www.americanshipper.com/.

0305-0548/$ - see front matter
http://dx.doi.org/10.1016/j.cor.2013.07.018

be random variables in stochastic handling time formulations. The fourth assumption refers to performance measurements or to uncertainty of the problem parameters; i.e., handling and arrival times. Most of the studies in the current literature focus on and vary in their assumptions on the first two characteristics and limited research has been published on analyses of the latter two characteristics.

In the setting of this paper, discrete berth space and uncertain vessel arrivals and handling times are assumed. We propose a mathematical formulation (extending the work by Konur and Golias [3]) that simultaneously minimizes the average and range of the total service time required to serve all the vessels at the terminals. The problem is initially formulated as a bi-objective optimization problem that contains two optimization problems in the definitions of each of the two objective functions. To overcome this complexity, the problem is decomposed into a bi-objective bi-level optimization problem. The revised formulation simplifies the problem and provides means to address both objectives in isolation. To solve the resulting problem, we propose a heuristic approach that combines exact and heuristic solution methods. The proposed scheduling strategy is compared to three commonly used scheduling strategies under arrival and handling time uncertainty: First Come First Serve Early Start (FCFS-S), First Come First Serve Early Finish (FCFS-F), and Expected Arrival and Handling Time Scheduling (EAHTS).

To the best knowledge of the authors, this study is the first in analyzing robustness in case of uncertain vessel arrival and handling times for the berth scheduling. The rest of the paper is structured as follows. Section 2 reviews the berth scheduling literature. Section 3 explains the proposed robust scheduling approach and provides the mathematical formulations. The proposed solution algorithm is explained in Section 4. Section 5 present results from a number of numerical examples and compares the proposed approach to three commonly used berth scheduling policies under arrival and handling time uncertainty. Summary of contributions, results and findings, and possible future research directions are noted in Section 6.

2. Literature review

A significant amount of research has been recently conducted on the berth scheduling problem (BSP) but only limited research has been published that deals with uncertainty when evaluating berth scheduling strategies. Golias [4] formulates a bi-objective mixed integer programming problem to simultaneously maximize the berth throughput and the reliability of a berth schedule. In this BSP, the vessel handling times are defined as stochastic variables and the author uses a combination of an exact algorithm and genetic algorithm based heuristics to solve the BSP with stochastic vessel handling times. Moorthy and Teo [5] address a BSP with continuous berth space and dynamic vessel arrivals to develop berth templates. The authors minimize the vessel waiting time and the cost of vessel transshipments. Their approach (as stated by the authors) is relevant only when a substantial number of vessels arrive periodically. Golias et al. [6] present a conceptual formulation for the discrete space dynamic vessel arrival BSP, where both vessel arrival and handling times are considered as stochastic variables. The authors present and compare the results of the following four heuristics based solution approaches: Markov Chain Monte Carlo based heuristic, online stochastic optimization based heuristic, deterministic solution based heuristic, and a combination of Monte Carlo with online stochastic optimization based heuristic. Zhou et al. [7] and Zhou and Kang [8] propose similar models dealing with uncertainty in vessel handling and arrival times by introducing probabilistic constraints. We note that formulations by Zhou et al. [7] and Zhou and Kang [8] constrain the vessel waiting times, which may lead to infeasibility (i.e., strict waiting time limits) or low quality solutions (i.e., high waiting time limits). Furthermore, their models are highly non-linear and assume normal distributions of the vessel arrival and handling times; whereas, use of Poisson, Uniform, truncated Normal, Gamma, or Erlang distributions are noted to represent vessel arrival and handling times in the literature [9,10].

Du et al. [11] study BSP with continuous space and propose a reactive feedback procedure to develop robust berth schedules addressing the uncertainty in vessel delays. The authors measure scheduling robustness with the cost of berthing a vessel at a non-preferred berth and the cost of delayed berthing and departure. These measures of robustness, nevertheless, may be conflicting as delayed berthing may result in early departures or assignment to a non-preferred berth may result in reduced waiting time and early departures. Gao et al. [12] address uncertainties in vessel delays and out-of-schedule berthing by proposing two types of strategies to develop a berth schedule: a proactive strategy is developed with a feedback procedure in case of vessel delays and a reactive strategy with a reassignment rule is proposed for out-of-schedule vessels. Xu et al. [13] propose a BSP formulation that models uncertainty in vessel delays and handling times by introducing the concept of buffers for the delays. This formulation, however, assumes continuous berth space, and; therefore, cannot be applied to the discrete case. In a recent study, Zhen et al. [14] apply the scenario-based modeling to berth scheduling. The authors introduce a number of scenarios for the vessel arrivals and operation times and develop a two-stage decision model, which is solved through a meta-heuristic. Han et al. [15] represent the uncertainty in vessel arrivals and handling times through probability density functions. When this type of an approach is adopted, it is common that simulation and heuristic procedures are used as solution methods.

The framework presented in this paper extends the current literature on BSPs by developing a proactive robust berth scheduling strategy that does not require knowledge or use of probability distributions for the vessel arrival and handling times. Among the common methods to introduce uncertainty in mathematical programming models are modeling through: (a) a scenario space, (b) a probability distribution, or (c) sets of upper and lower bounds. Modeling uncertainty through a scenario space is usually appropriate if the uncertainties inherent in the processes have been previously observed for relatively long periods of time and a historical set of data has been collected. This scenario-driven formulation approach usually leads to two-stage and multistage models of stochastic programming.

Modeling uncertainty in mathematical problems through introduction of upper and lower bounds on the variables has been extensively studied by Ben Tal and Nemirovski [16] and is adopted in this paper. This type of approach falls under the area of robust optimization. Solution techniques for these types of problems usually lead to the semi-definite and conic optimization models, which are generally non-linear. The term “robust optimization” has also been attributed to variable dissimilar formulations, all converging to the common aim of producing solutions which will not be catastrophic, in terms of costs, following the realization of the random variables. Next we present the motivation for this study and the problem formulation.

3. Model formulation

As noted previously, robustness of a berth schedule is crucial for the overall performance of a container terminal [13]. A berth schedule can be defined to be robust in case the total time