European Journal of Operational Research 255 (2016) 380–387

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Production, Manufacturing and Logistics

Optimal policies for the berth allocation problem under stochastic nature

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ARTICLE INFO

Article history:
Received 29 May 2015
Accepted 15 April 2016
Available online 22 April 2016

Keywords:
Pricing
Inventory
Return and expediting
Stochastic dynamic programing
Optimization

ABSTRACT

Key purpose of container terminals is to serve container vessels. Container vessels may be of different types such as large deep-sea vessels or feeders and barges. Container terminal operators have to deploy intelligent strategies for the allocation of their limited resources to the calling vessels of those different types. The presence of uncertainty in the real processing of the operational schedules and arrival of vessels adds to the complexity of the already multifaceted problem. An inefficient decision in the berth allocation phase affects all the other applications connected to this and may increase the service period and costs. In this study, we propose a framework based on stochastic dynamic programing approach to model the berth allocation problem and characterize optimal polices under stochastic arrival and handling times for different types of calling vessels. We find that the optimal control policy is of threshold type depending on the number of vessels in a certain berth group. The derived policies can be used at container terminals for the optimal use of their berthing facilities.

1. Introduction

Due to the trend towards sea transportation, efficient port management has become a major issue for the port owners and shipping companies. Typical operations in a port consist of allocation of arriving vessels to berths, allocation of quay cranes to docked vessels at the quayside, routing of internal transportation vehicles, storage space assignment, and gantry crane deployment at the yard side. The allocation of arriving vessels to berths is referred to as the Berth Allocation Problem (BAP). Berth management drives the port management process and the major challenge for this process is to determine the optimal allocation strategy to the calling vessels. An important fact for the terminal operators to consider is the different types of calling vessels. Container terminals not only serve deep-sea vessels but also vessels, such as feeders and barges. Indeed, considering the intention of terminals to stay competitive in the market, these vessels of different types cannot be treated equally. Together with the revenue considerations and navigational reasons, deep sea vessels receive higher attention from the container terminals. Due to limited capacity, it is also possible that some vessel calls may need to be forwarded to other ports/terminals based on collaboration policies among ports. Therefore, the decision maker needs to employ intelligent strategies when allocating their scarce resources to those different types of vessels. Previous literature has also underlined the importance of employing flexible vessel-berth-order allocation rather than the First-Come-First-Served (FCFS) rule for higher productivity (Imai, Nishimura, & Papadimitriou, 2008).

The fact of serving different types of vessels is not the only aspect that makes the berth allocation problem a complex one. The presence of uncertainty in the real processing of the operational schedules further adds to the complexity of the problem. For instance, in practice, the actual arrival times of vessels are highly uncertain: only half of the vessels arrive on time (Consultants, 2008). Indeed, the solutions of the deterministic berth allocation problem can only be applied in an ideal plant, where cranes are perfectly reliable, container information is accurate, vessel arrival times are precisely known, task handling times are constant and weather is fairly predictable. This of course is far from reality and, thus, the deterministic problem has to be extended to a stochastic version. Mentioned uncertainties will result in the change of the initial plans and both the port owners and the shipping companies will burden extra costs. Therefore it is essential for decision makers to consider the impact of uncertainties to some extent and develop promising methods while making plans.

The berth allocation problem, as being one of the most crucial issues in container terminals, has received a lot of attention from researchers. Approaching the problem considering the practical aspects is important as the decisions given at the berth allocation stage has a direct impact on the following operations within the container terminal. Most literature assumes a deterministic setting

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http://dx.doi.org/10.1016/j.ejor.2016.04.029
0377-2217/

where information as to the vessel arrivals and handling times are precisely available. Previous work reflecting the stochastic nature has not yet provided analytical solutions and the structure of optimal policies for the berth allocation problem. In this work, we aim to fill this gap in the literature by focusing on the berth allocation problem incorporating the uncertainty in vessel arrival times and handling times. The setting in practice where different types of customers need to be served are together reflected in the novel approach. Our contributions are to propose a framework based on stochastic dynamic programing approach to model the berth allocation problem and characterize optimal polices. For a base model, we find that the optimal control policy is of threshold type depending on the number of vessels in a certain berth group. If the number of vessels in a berth group is below the threshold, then the vessel should be allocated to this berth group; otherwise, it should be allocated to the other berth group. Further, we find that a similar policy can be applied to more general situations, including possibility of forwarding vessels calls, multiple berths at each berth group, and different priorities of vessels. We may conjecture that such a threshold policy is robust.

The remainder of this paper is organized as follows: Next section will put forward the related literature. Following, in Section 3, the model will be proposed. Optimal policy structures will be presented in Section 4. Experiments based on a case at the Port of Izmir will be provided in Section 5. Section 6 will put forward the extensions to the model so as to effectively reflect the different settings in a container terminal. Finally, the last section will be devoted to conclusions and future work.

2. Literature review

Berth allocation problem deals with the allocation of arriving vessels to berths. Without proper berth allocation, it is impossible to activate the subsequent activities competently. Researchers in the literature have brought different approaches to the solution of the problem. In line with its importance, significant amount of research has focused on container terminal operations (Carlo, Vis, & Roodbergen, 2015; Stahlbock & Voß, 2008; Steenken, Voß, & Stahlbock, 2004; Theofanis, Boile, & Golias, 2009; Vis & De Koster, 2003). Unfortunately, majority of the studies assume a deterministic structure and published works reflecting the stochastic nature are relatively very few. In this review, those studies that capture the stochastic nature of the berth allocation problem will be put forward. Next, studies that reflect the need for differentiating among different vessel types will be summarized.

For the stochastic berth allocation problem, (Moorthy & Teo, 2006) developed a framework to create robust berth allocations. The problem is modeled as a bi-criteria optimization problem and solved using simulated annealing algorithm. As stated by the authors, the template is relevant only when a substantial number of vessels arrive periodically and within the same period. Du, Xu, and Chen (2010) proposed a feedback procedure for the robust berth allocation problem with stochastic vessel delays similarly using the simulated annealing algorithm. To cope with the uncertainties on vessel delays, some delay scenarios are used, with the assumption that all delay scenarios happen with identical probabilities. Golias, Boile, and Theofanis (2007) proposed a sole conceptual formulation and four solution approaches for the berth allocation problem: Markov chain Monte Carlo based heuristic, stochastic online scheduling based heuristic, deterministic based heuristic and genetic algorithm based approach. Han, Lu, and Xi (2010) implemented a simulation based genetic algorithm approach to solve the integrated berth and quay crane scheduling problem with uncertainty in vessel arrival and operation times. The aim in their study is to minimize the sum of expected value and standard deviation of the service time and the weighted tardiness of the vessels. Hendriks, Laumanns, Lefeber, and Udding (2010) study the robust berth planning problem by considering arrival windows rather than expected arrival times. They propose a mixed integer linear program to find a robust berth plan that minimizes the crane reservation and show that handling time of vessels is highly dependent on the actual arrival time of vessels. Zhen, Lee, and Chew (2011) approached the berth allocation problem under uncertainty by formulating several scenarios and aiming at minimizing the total cost of baseline schedule and expected cost of recourse. Xu, Chen, and Quan (2012) allocated constant buffer times to all vessels to produce robust berth allocation plans. The problem is solved by a scheduling algorithm that integrates simulated annealing and branch-and-bound algorithms. Zhen and Chang (2012) defined robustness as weighted sum of the free slack times in the berthing schedule. A bi-objective model is proposed that minimizes cost and maximizes robustness where weights are determined according to the vessel priorities. Karafa, Golias, Ivey, Saharidis, and Leonardos (2013) formulated the berth allocation problem with stochastic handling times as a bi-objective problem. They used an evolutionary-algorithm based heuristic and a simulation-based Pareto pruning algorithm to solve the problem. However, the arrival times are assumed as deterministic in their model. Regarding studies employing queuing theory we may refer to Legato and Mazza (2001) and Canonaco, Legato, Mazza, and Musmanno (2008). The data used in the studies are based on Gioia Tauro Container Terminal in Italy. First, a queuing network model is proposed and described for the berth allocation problem. Due to the complexity of the problem using an analytical approach to the solution is discouraged and discrete-event simulation model is performed. Golias, Portal, Konur, Kaisar, and Kolomvos (2014) studied a berth scheduling problem with uncertain vessel arrival and handling times. With the objective of minimizing the range of the total service time between the worst and the best performances, the authors formulated a bi-objective optimization problem to obtain a robust schedule and also designed a heuristic to compute the schedule. Zhen (2015) considered the berth allocation problem with uncertain dwell times of ships. The author proposed a stochastic programming formulation with an objective of minimizing the deviations of ship's scheduled berthing time from their expected ones. Further, the author designed some meta-heuristics to solve the models. However, the previous literature has not analytically characterized the structure of optimal policy for the berth allocation problem. Our paper focuses on the development of such policies through optimal controlling of queuing systems. Under the assumption of exponential queueing system, (Lippman, 1975) first developed a uniformization technique that can formulates the problem of controlling a multiple-server queue into a finite-horizon stochastic dynamic programing. Based on such a technique, Hordijk and Koole (1992) studied the assignment problem to multiple single-server queues in parallel. The authors find out the conditions under which it is cost-efficient to assign customers to a faster server with a shorter queue. Koole (1998) characterized the structure of optimal policies of resource-sharing queueing systems. In the healthcare sector, Chao, Liu, and Zheng (2003) derived an optimal static resource allocation rule for a multiple-single-server queueing system by allowing customer switching. Different from the above papers, we consider the dynamic optimal policies of various scenarios with multiple-server queues in berth groups.

We will continue our literature review with studies that recognize the presence of applying different strategies for different vessel classes within the berth allocation problem. A genetic algorithm based heuristic to solve the formulated nonlinear problem by defining priorities through assigning weights to the vessels was proposed by Imai, Nishimura, and Papadimitriou (2003). In Guan and Cheung (2004) a weight coefficient for each vessel is defined