European Journal of Operational Research 247 (2015) 928–944

Contents lists available at ScienceDirect

European Journal of Operational Research

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

Innovative Applications of O.R.

Tactical berth allocation under uncertainty

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ARTICLE INFO

Article history:
Received 17 September 2014
Accepted 30 May 2015
Available online 6 June 2015

Keywords:
Scheduling
Berth allocation
Container terminals
Uncertainty

ABSTRACT

The tactical berth allocation problem (BAP) concerns the allocation of favorite berthing positions to ships that periodically call at the terminals. This paper investigates the tactical-level berth allocation scheduling models. First a deterministic model for tactical BAP is formulated with considering the periodicity of schedule. However, in reality, the number of containers that need to be handled (discharging & loading) for each ship is uncertain in the ship's future periods. Thus for the tactical BAP, there is significant uncertainty with respect to the operation time (dwell time) of ships, which further complicates the traditional berth allocation decisions. From stochastic perspective, this paper proposes both a stochastic programming formulation that can cope with arbitrary probability distributions of ships' operation time deviation, and a robust formulation that is applicable to situations in which limited information about probability distributions is available. The relationship between the two models is also investigated in an analytic way. Some meta-heuristic algorithms are suggested for solving the models. Numerical experiments are performed to validate the effectiveness of the proposed models and the efficiency of the proposed solution algorithms. The experiments also compare the above stochastic programming formulation and the robust formulation models, as well as evaluate their potential benefits in practice. This study finds that the robust method can derive a near optimal solution to the stochastic model in a fast way, and also has the benefit of limiting the worst-case outcome of the tactical BAP decisions.

1. Introduction

The berth allocation problem (BAP) is an important issue for the operations management in container terminals. It is mainly referred to the assignment of quay space and service time to ships that have to be discharged and loaded at a terminal. For a comprehensive overview on BAP, we refer to the review work given by Bierwirth and Meisel (2010). The extant literature deals largely with the operational-level BAP in deterministic environments with complete information. However, this paper investigates the tactical-level BAP, which is also known as home berth template planning (Moorthy & Teo, 2006). The tactical BAP arises in large container terminals and concerns the allocation of favorite berthing positions to ships which periodically call at the terminals (Giallombardo, Moccia, Salani, & Vacca, 2010). This paper studies how to obtain a robust berth allocation schedule under stochastic operation time (dwell time) of ships. Different from the deterministic operational-level BAP, the robust planning of tactical BAP supports the decisions made by port operators in the negotiation process with shipping liners. In this process, the port operators should try to satisfy the expected berthing time of ships, but also incorporate a degree of anticipation of uncertainty during the schedule's execution. From the stochastic perspective, this paper proposes both a stochastic programming formulation that can cope with arbitrary probability distributions of ships' operation time deviations, and a robust formulation that is applicable to situations in which limited information about probability distributions is available. We compare the above two models and evaluate the potential benefits in practice. On the basis of numerical experiments, we find that the robust method can derive a near optimal solution to the stochastic model in a fast way, and also has the benefit of limiting the worst-case outcome of the tactical BAP decisions.

The remainder of this paper is organized as follows. Section 2 reviews the related works. In Section 3, we provide the background of the tactical BAP, and propose a deterministic model with considering the periodicity of schedule. Section 4 presents a stochastic programming model that takes account of random extra operation time of ships. In Section 5, some meta-heuristic algorithms are suggested for solving the model. Section 6 addresses a robust formulation model, and also discusses the potential relationship between the robust model and the stochastic programming model. Section 7 reports the numerical results and management implications based on the experiments using some sets of real world like instances. Some possible extensions of this study are also discussed in Section 8. Closing remark and summary are then outlined in the last section.

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http://dx.doi.org/10.1016/j.ejor.2015.05.079

2. Related works

For a comprehensive overview on container terminal operations and maritime logistics, see the review work given by Vis and de Koster (2003), Steenken, Voß, and Stahlbock (2004), Stahlbock and Voß (2008), Fransoo and Lee (2013). This study is related to the berth allocation problem (BAP), which is very important for ports' operation management and is also the basis for making other plans on container scheduling decisions by shipping liners (Choi, Lee, Leung, Pinedo, & Briskorn, 2012). BAP has attracted a large attention in academic researches. Imai, Nagaiwa, & Chan (1997) addressed the static BAP (SBAP) in commercial ports. Imai, Nishimura, and Papadimitriou (2001) extended the SBAP to dynamic BAP (DBAP), based on which Monaco and Sammarra (2007) proposed a compact reformulation. BAP can be classified into two types: discrete and continuous problems (Imai, Sun, Nishimura, & Papadimitriou, 2005). As to the discrete problems, the quay is partitioned into a number of sections (berths), where one ship could be handled at a time. Whereas in the continuous problems, ships could be served wherever empty spaces are available, which resembles a two-dimensional un-rotated bin packing problem (Lim, 1998). As to the solution methodology for the continuous BAP, Kim and Moon (2003) proposed a simulated annealing method. Park and Kim (2002) employed a sub-gradient optimization method. Guan and Cheung (2004) developed a heuristic with minimizing total weighted completion time. Wang and Lim (2007) developed a beam search method for BAP. Nishimura, Imai, and Papadimitriou (2001) proposed a genetic algorithm for BAP to obtain a good solution with small computational effort. Imai, Nishimura, Hattori, and Papadimitriou (2007) investigated BAP for the indented berths, where mega-containerships could be served from two sides. Cordeau, Laporte, Legato, and Moccia (2005) studied BAP in some specific quay which consists of variable berths. Hansen, Oguz, and Mladenovic (2008) proposed a variable neighbor search method for BAP, in which vessels' handing time and cost depend on berthing positions. Lee and Chen (2009) developed a heuristic method for solving the BAP. Besides the above studies mainly based on mathematical programming, some stduies are via the discrete event simulation, e.g., Legato and Mazza (2001). Moreover, the simulation optimization technique is recently utilized to optimize the tactical and operational BAP decisions in an integrated way (Legato, Mazza, & Gullì, 2014). Randomness in discharge/loading operations and quay crane (QC) assignment were also considered. In their study, mathematical programming model and simulation model are used for the tactical and the operation level decisions, respectively. Another stream of the BAP studies is about the integrated planning of berth allocation and QC assignment. Park and Kim (2003) developed a two-phase solution procedure, and a dynamic programming technique. Meisel and Bierwirth (2009) treated the BAP-QC assignment as a multi-mode resource constrained project scheduling problem. Imai, Chen, Nishimura, and Papadimitriou (2008) considered that when one vessel is handling, QCs cannot pass or bypass from its one side to the other. A latest review on BAP was given by Bierwirth and Meisel (2010). Wang, Meng, and Liu (2013) presented a second-order cone programming based method to capture fuel costs associated with ship delays. In the following, we discuss some articles that are more relevant to this study.

The concept of tactical-level berth allocation planning was first mentioned in academic literature by Moorthy and Teo (2006). In their study, the tactical BAP is named as berth template planning, which maximizes the service level that is related to the percentage of ships whose mooring operations commence within 2 hours of arrival, and minimizes the connectivity cost that is related to the distances between berths within ship transshipment groups. In their study, the robustness of the berth template was taken into account to handle the uncertainties in the reality. Cordeau, Gaudioso, Laporte, and Moccia (2007) studied the service allocation problem that is a tactical problem arising in the Gioia Tauro transshipment hub. A generalized quadratic assignment model was formulated to minimize the containers rehandling operations in yard. On the basis of this study, Giallombardo et al. (2010) investigated the tactical discrete BAP and QC assignment problem. A novel concept 'QC-profile' was proposed to facilitate the combination of BAP and QC assignment problem. In the objective function, they took account of yard cost that is related to the distances between the incoming and outgoing berths. For the above problem, Vacca, Salani, and Bierlaire (2013) proposed an exact branch and price algorithm, which can solve problem cases with 20 ships and five berths. By following the study of Giallombardo et al. (2010), Zhen, Chew, and Lee (2011b) integrated the tactical berth allocation planning (also known as berth template) with the yard template planning. In this way, more detailed factors on yard transportation can be considered in the tactical BAP. The above four studies mainly apply in transshipment hubs. Whereas, the problem background of this study is oriented to generic ports. It should be noted that the BAP studies for transshipment hubs are more complex than the BAP studies for generic ports, because the former ones need to consider the minimization of the distance between each pair of ships' berthing positions when there are a lot of transshipped containers between the pair of the two ships (Giallombardo et al., 2010). For model formulation, this study does not consider these factors about distances between each pair of ships with transshipment activities. Recently, Meisel and Bierwirth (2013) proposed a framework for aligning all decisions of berth allocation, quay crane assignment, and quay crane scheduling problems in an integrative manner. Robenek, Umang, Bierlaire, and Ropke (2014) designed an exact branch-and-price algorithm to solve the integrated berth allocation and yard assignment problem in bulk ports. Hendriks, Lefeber, and Udding (2013) proposed a tactical level decision model for simultaneous berth allocation and yard planning. A heuristic method was designed to solve the proposed mixed integer programming model. Wang, Liu, and Qu (2015) designed a collaborative mechanism for tactical-level berth allocation. This study is a major breakthrough in port operations. The mechanism guarantees both system optimality and fairness between shipping lines.

For the uncertainty in BAP, Moorthy and Teo (2006) highlighted this issue; but they did not propose a mathematical model that explicitly involves the uncertainty in the berthing activities. Han et al. (2010) developed a MIP model for berth allocation and QC assignment under stochastic arrival time and operation time; a genetic algorithm based meta-heuristic was suggested for solving the model. Zhen, Lee and Chew (2010a) also studied the BAP under stochastic arrival and operation times. A two-stage stochastic programming model and a simulated annealing based meta-heuristic were proposed. The main difference between these two studies lies in: Zhen's model is about continuous BAP, while Han's model is discrete BAP. Hendriks, Laumanns, Lefeber, and Udding (2010) proposed an arrival window agreement based robust cyclic berth planning model to minimize the maximal crane capacity reservation ever required. Hendriks, Armbruster, Laumanns, Lefeber, and Udding (2012) extended the cyclic berth planning problem from the environment of single terminal to the system of multiple terminals. Both the balance of the QC workload over terminals and the minimization of inter-terminal transportation were considered in the objective of their model.

By comparing with the state-of-the-art literature, this paper makes a more comprehensive study on the tactical BAP. The factor of periodicity is explicitly considered in the stochastic programming formulation model and the robust formulation model. The relationship between the two models is investigated in an analytic way.

3. Deterministic model for tactical BAP

The tactical berth allocation planning supports the decisions made by port operators in the negotiation process with shipping