Computers & Industrial Engineering 78 (2014) 84–94

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Integrating tactical and operational berth allocation decisions via Simulation–Optimization ☆

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ARTICLE INFO

Article history:
Received 24 October 2012
Received in revised form 10 January 2014
Accepted 5 October 2014
Available online 16 October 2014

Keywords:
Port logistics
Berth planning
Simulation optimization
Metaheuristics

ABSTRACT

The berth allocation problem (BAP) arising in maritime container terminals has received great attention in the literature over recent years. It has been largely modeled as an integer mathematical programming formulation to be adopted at a tactical level, where detailed equipment and manpower schedules, as well as real-time operational conditions are not explicitly modeled. In this paper, decision making for the BAP is supported by integrating two separate models into a Simulation–Optimization framework: a mathematical programming model at the tactical level and a simulation model at the operational level. Specifically, the framework uses a beam search heuristics to obtain a weekly plan at the tactical level, followed by a simulated annealing based search process to adjust allocation decisions at the operational level. At this level, randomness in discharge/loading operations is taken into account and modeled by an event-based Monte Carlo simulator. A non-standard ranking and selection procedure is used to compare alternative BAP solutions, within the Simulation–Optimization procedure, in order to reduce the related number of simulation runs required. Numerical experiments performed on real instances show how, under conditions of uncertainty and variability, the tactical solution returned for the BAP requires tuning at the operational level.

1. Introduction

The main goal of a maritime container terminal's business strategies and overall management is to prospect new clients and maintain existing ones by providing them with high-quality and cost-effective services focused around vessel discharge/loading (D/L) operations. During the practical exercise of the above pursuit, a terminal is assisted by decision support systems that, in turn, are fed by various levels of information issued by different inner-departments at different times. For instance, mid-term or tactical information is released as a result of major resource planning such as the assignment of berth windows, crane productivity targets or yard stacking areas, while short-term or operational information is acquired during the actual performance of operations and may be affected by the occurrence of unforeseen events such as delays in vessel arrival, berthing and container handling. To cope with and provide an uninterrupted company workflow that embodies multiple information sources, a seamless integration between tactical and operational dimensions becomes a priority for the performance optimization of any logistic process.

In this paper we propose a specialized framework to manage both tactical and operational planning issues in an integrated way when facing the berth allocation problem (BAP) in port logistics. Integration is implemented via Simulation–Optimization (SO) by inserting a simulation engine (evaluation process) in an optimization algorithm (search process). The object of the framework is to enable the tuning of the tactical solution (berth template) returned for the BAP when process disturbances and equipment disruptions overcome in the operational stage. The tuning of the tactical solution is performed by a simulated annealing based (global) search procedure acting as a uniformly distributed sampling strategy of the entire combinatorial set of berth templates. This results in a cumbersome iterative process where, at each iteration, a neighboring solution is randomly generated and then compared with the current best solution with respect to the average value of the fixed performance metric estimated by simulation replications. Inspired by statistical techniques of data reusage, we reduce the computational burden of a classical two-stage ranking and selection procedure for solution comparison by adopting a low-variance moving-average estimator for the sample mean.

A major benefit of the integrated approach lies in the possibility of assessing the robustness of a BAP tactical template. A solution is

☆ This manuscript was processed by Area Editor Simone Zanoni.

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http://dx.doi.org/10.1016/j.cie.2014.10.003
0360-8352/

commonly defined robust when its feasibility is kept and its cost is acceptably affected by changes of the input data. In the BAP, robustness should be measured in terms of the capability of returning feasible adjustments that bear costs savings for the terminal in the management of vessel arrival instants uniformly distributed within specific time windows, as well as the capability of a BAP template to tolerate unavoidable delays in the completion times of discharge/loading operations performed on berthed vessels.

The paper is organized as follows. In Section 2 the literature on the BAP is reviewed and the problem is discussed by focusing on both the tactical and operational views. In Section 3 the framework for integrated decision making is presented by describing how feasible BAP solutions are generated, evaluated and selected. Numerical experiments based on real-life data are presented in Section 4, while conclusions are drawn in Section 5.

2. The berth allocation problem

Logistics at maritime container terminals amount to three major processes (Vis & De Koster, 2003): (i) vessel acceptance, maneuvering and berthing, (ii) container D/L operations and (iii) container picking-storage-retrieval in the yard area. All these processes involve the use of expensive resources for container handling and may be successfully supported by mathematical models (Stahlbock & Voß, 2008; Steenken, Voß, & Stahlbock, 2004) and simulation procedures (Bielli, Boulmakoul, & Rida, 2006; Legato & Mazza, 2001; Yun & Choi, 1999) for evaluating and optimizing their performance in resource allocation and activity scheduling. The berth allocation problem (BAP) is focused here. Key BAP modeling and solving from literature on both the tactical and operational level are reported below.

At the tactical level of decisions, a continuous, yet limited quay length is organized into smaller segments, each bearing a different water depth, to be optimally assigned to incoming vessels in order to perform container D/L operations. Each vessel is represented by a space–time rectangle to reflect its space–time occupancy within the template. Whatever the berth representation – a discrete set of small berthing segments or a continuous and unique long segment – the planning goal is to achieve a good matching between container storage positions on the yard versus container D/L positions on the berth (home berth locations) in order to minimize the distance to cover during container transfer.

In previous literature, both the discrete and continuous approaches to berth modeling at a tactical level have been pursued under the common assumption that both the arrival time and processing time per vessel are known without any uncertainty (Cordeau, Laporte, Legato, & Moccia, 2005; Guan & Cheung, 2004; Imai, Nishimura, & Papadimitriou, 2001; Imai, Sun, Nishimura, & Papadimitriou, 2005; Kim & Moon, 2003; Lim, 1998). Some papers concentrate on improving computational performance of the heuristic methods proposed for problem solving at the tactical level (Buhrkal, Zuglian, Ropke, Larsen, & Lusby, 2009; Hansen, Oguz, & Mladenovic, 2008; Lee & Chen, 2009; Wang & Lim, 2007), while others are devoted to integrating berth allocation with the subsequent decision of assigning the proper number of cranes, hour by hour, to each vessel during D/L operations (see Bierwirth & Meisel, 2010 for an overview). Further research efforts aimed at a deeper integration between berth allocation and crane management (Liu, Wan, & Wang, 2006; Song, Cherrett, & Guan, 2012; Vacca, Salani, & Bierlaire, 2013) or between berth allocation decisions and yard planning (Zhen, Chew, & Lee, 2011a) may also be found in recent literature.

Stochastic issues of the BAP are addressed by Moorthy and Teo (2006). Two separate space and time constraint graphs are adopted to manage the combinatorial complexity of the rectangle packing problem underlying the optimum berth template in continuous space and time. As for the space side, the minimization of the connectivity cost between berthing points along the berth and storage points in the yard is confined in a separate mathematical programming model. On the time side, these authors estimate the expected berthing time under normality assumptions for both vessel arrival times and processing times by using techniques from stochastic project scheduling.

A few more recent papers (Hendriks, Laumanns, Lefeber, & Udding, 2010; Song et al., 2012; Zhen & Chang, 2012; Zhen, Lee, & Chew, 2011b; Zhou & Kang, 2008) focus on the problem of managing the uncertainty in vessel arrival times and operation times by resorting to basic ideas from stochastic programming and robust optimization. Uncertainty is usually considered in the general case where no probability distributions can be inferred from real data pertaining to vessel arrivals and operation times.

Precisely, Zhou and Kang (2008) adopt a discrete berth representation, with a given number of service points along the quay, and propose an integrated berth and quay-crane model by using a stochastic 0–1 programming model aimed at minimizing the waiting time for both berth and crane assignment at the operational level. Vice versa, Hendriks et al. (2010) remark that container terminal operators and shipping lines agree upon time windows on vessel arrivals and develop a planning model that captures the uncertain arrival instant within the above window. Robustness is considered in berth planning as the capability of returning a feasible assignment of crane capacity, as required by each vessel, for each arrival scenario where all vessels arrive within their time window. This window is obtained by simply shifting the arrival time of each vessel with the goal of minimizing the maximal crane capacity reservation that would result from adopting a plan based on fixed arrival times. Zhen et al. (2011b) pursue both a proactive strategy and a reactive recovery strategy to generate and adjust a robust-time berth plan aimed at remaining feasible at the minimum objective function deterioration. These authors propose a stochastic re-formulation, i.e. under a finite set of discrete scenarios, of the deterministic IP model of the continuous BAP defined by Kim and Moon (2003). The prohibitive computational complexity of the resulting mathematical problem against real-size problems is tackled by adopting a sequence based (heuristic) method to determine a baseline schedule followed by a series of recovery schedules. In a more recent work (Zhen & Chang, 2012), the adoption of time buffers between vessel arrivals is at the basis of another reformulation of the previous cited BAP model due to Kim and Moon (2003) to deal with uncertainty. The resulting model is a bi-objective optimization problem, aimed at minimizing the classical objective function while maximizing the robustness, defined as a weighted sum of the free slacks. Non-dominated solutions are obtained by a heuristic procedure and their performances are evaluated against stochastic scenarios generated by a simulator. Finally, the idea of using a time buffer as a measure of robustness is still kept by Xu, Chen, and Quan (2012) in the constraints structure of the BAP formulation due to Kim and Moon (2003). The total departure delay of vessels is adopted as the service measure to be optimized, with suitable weights per different vessels. A berth scheduling algorithm that integrates a simulated annealing procedure and a branch-and-bound algorithm is used and validated through simulation.

As one may recognize, uncertainty has been dealt with and represented at the tactical level through possible scenarios or resorting to robust optimization ideas and, therefore, inserting time buffers. Rather, in this paper, a different conception is adopted according to which the BAP should be suitably viewed at both a tactical and operational level, in an integrated way, but by two separate models: a mathematical programming model at