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Discrete Optimization

Optimal berth allocation and time-invariant quay crane assignment in container terminals

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ABSTRACT

Due to the dramatic increase in the world's container traffic, the efficient management of operations in seaport container terminals has become a crucial issue. In this work, we focus on the integrated planning of the following problems faced at container terminals: berth allocation, quay crane assignment (number), and quay crane assignment (specific). First, we formulate a new binary integer linear program for the integrated solution of the berth allocation and quay crane assignment (number) problems called BACAP. Then we extend it by incorporating the quay crane assignment (specific) problem as well, which is named BACASP. Computational experiments performed on problem instances of various sizes indicate that the model for BACAP is very efficient and even large instances up to 60 vessels can be solved to optimality. Unfortunately, this is not the case for BACASP. Therefore, to be able to solve large instances, we present a necessary and sufficient condition for generating an optimal solution of BACASP from an optimal solution of BACAP using a post-processing algorithm. In case this condition is not satisfied, we make use of a cutting plane algorithm which solves BACAP repeatedly by adding cuts generated from the optimal solutions until the aforementioned condition holds. This method proves to be viable and enables us to solve large BACASP instances as well. To the best of our knowledge, these are the largest instances that can be solved to optimality for this difficult problem, which makes our work applicable to realistic problems.

1. Introduction

The proportion of containerized trade in the world's total dry cargo has increased from 5.1% in 1980 to 25.4% in 2008 (UNCTAD, 2009). Containers provide a reliable and standardized means of transportation, which results in shorter transit times, possibility of using multiple modalities and eventually in reduced shipping and handling costs. As a result of these factors, container traffic has increased by 53.3% between years 2000 and 2010, 11% of which is attributed to year 2010 alone (UNCTAD, 2010). This rate of increase has made efficient management of container terminal operations crucial, resulting in a significant amount of research from an Operations Research point of view (Steenken, Voß, & Stahlbock, 2004; Stahlbock & Voß, 2008). Container terminal operations are very complicated, requiring close coordination of ships, cranes, trucks, storage space and personnel. Huge data and computational resource requirements make it impractical to consider decision problems on the entire set of operations at once. Instead, container terminal operations are typically grouped as seaside, transfer and yard operations and the corresponding problems are investigated separately (Vis & de Koster, 2003). In this paper, we concentrate on integrated seaside operations (Meisel, 2009), and refer the reader to the recent work of Vacca (2010) for more information about transfer and yard operations.

Various problems in seaside operations have been investigated in the literature. One of the first lines of research on analysis of seaside operations investigates the applications of queuing models in port investment decisions for container berths (Edmond & Maggs, 1978). However, more recent research on seaside operations has focused on solving operational planning problems. In particular, the berth assignment problem (BAP) deals with the determination of optimal berthing times and locations of ships such that incoming vessels arrive and depart within their allowed time windows and no two vessels occupy the same berth-time segment simultaneously (Lai & Shih, 1992; Brown, Lawphongpanich, & Thurman, 1994). The quay crane assignment problem (CAP) deals with allocating cranes to vessels such that each vessel is assigned to a number of cranes within some specified bounds, and the total number of cranes is not exceeded (Steenken et al., 2004). CAP can be extended in such a way that the specific cranes used for the service of vessels are also determined. This problem is referred to as CAP (specific) in Bierwirth and Meisel (2010), which we name as CASP. This means that in addition to the number of cranes assigned to a vessel, it is also determined in CASP which individual quay cranes serve that vessel. More detailed constraints regarding physical alignment of

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cranes along a rail are considered as well (Daganzo, 1989; Peterkofsky & Daganzo, 1990). We refer the reader to Bierwirth and Meisel (2010) for a detailed literature survey on seaside operations.

BAP and CASP can be solved sequentially as suggested by the initial research. However, the distribution of cranes to vessels has a direct effect on the vessels' processing times. Therefore, later research has focused on integrating these problems. To the best of our knowledge, first attempts for integration are due to Daganzo (1989), Peterkofsky and Daganzo (1990), where the authors unify CAP and quay crane scheduling problem (CSP) called CACSP. The aim of CSP is to find a detailed schedule for each crane by taking into account all unloading and loading operations with task precedence constraints. Recently, Tavakkoli-Moghaddam, Makui, Salahi, Bazzazi, and Taheri (2009) propose a new mixed-integer programming formulation and a heuristic solution algorithm for CACSP. The integration of BAP and CAP into berth allocation and quay crane assignment problem (BACAP) has received more attention (Blazewicz, Edwin Cheng, Machowiak, & Oguz, 2011; Bierwirth & Meisel, 2010; Meisel & Bierwirth, 2005; Meisel & Bierwirth, 2009a, 2009b; Hendriks, Laumanns, Lefeber, & Udding, 2008; Giallombardo, Moccia, Salani, & Vacca, 2010; Liang, Huang, & Yang, 2008). In addition to proposing solution algorithms for BACAP, Park and Kim (2003) and Imai, Chen, Nishimura, and Papadimitriou (2008) propose post-processing approaches for the determination of the specific cranes used. Rashidi (2006) and Theofanis, Golias, and Boile (2007) develop an integrated mathematical programming formulation for BACAP that yields the optimal berthing times and positions of the vessels in addition to the number of cranes.

The BACAP model proposed in Liu, Wan, and Wang (2006) is weaker in the sense that the authors determine optimal vessel berthing times, crane numbers and specifications, but an optimal solution does not include any information about berthing positions. Besides, they preprocess CSP to generate possible handling times for each vessel and each assignable number of cranes. The same approach is adopted by Meier and Schumann (2007), Meisel (2009), Meisel and Bierwirth (2013) and Ak (2008). Meier and Schumann (2007) try to achieve this by functionally integrating their integrated CACSP model with BAP. However, Meisel (2009) and Meisel and Bierwirth (2013) functionally integrate BACAP with CSP: crane schedules are determined according to the berthing times while crane assignments are obtained by solving an integrated BACAP model. In his work on the optimal planning of the seaside operations, Ak (2008) develops a mixed-integer linear programming (MILP) model that integrates BAP, CAP and CSP. His model calculates optimal berthing times, berth allocations and crane number assignments of the vessels, and crane schedules simultaneously for given specific crane assignments, which makes the presented integration as the deepest of the available ones. However, the author suggests a Tabu search heuristic since his model can only handle very small problem instances. Zhang, Zheng, Zhang, Shi, and Armstrong (2010) focuses on the integration of BAP and CASP (which we call BACASP in the sequel). Due to the complexity of their formulation, a commercial solver package for MILP problems can only deal with up to three vessels within 1 one hour of CPU time. Therefore, the authors apply a method based on Lagrangian relaxation and sub-gradient optimization to solve the problem.

In this work we follow this line of research and formulate two new MILP formulations deeply integrating first BAP and CAP (BACAP), and then BAP and CASP (BACASP). Both of them consider a continuous berth layout where vessels can berth at arbitrary positions within the range of the quay and dynamic vessel arrivals where vessels cannot berth before the expected arrival time. The crane work plan found by solving the BACASP formulation determines the specific crane allocation to vessels for every time period. As a result, BACASP may be seen as a deep integration of BAP and CASP for which there is no study according to the recent survey of Bierwirth and Meisel (2010). In the work plan obtained by solving the BACASP model, when two vessels are at the berth at the same time, cranes are assigned to vessels in such a way that the one having a position before the other gets cranes such that the cranes of the former are positioned before those of the latter. We propose a necessary and sufficient condition for obtaining an optimal solution of BACASP from an optimal solution of BACAP by a post-processing algorithm. We also develop an exact solution algorithm for the case where this condition is not satisfied. This is a cutting plane algorithm that generates cuts for the BACAP formulation until the condition is satisfied. Then it becomes possible to apply the aforementioned post-processing algorithm and obtain an optimal solution of BACASP. Experiments show that cutting plane algorithm finds optimal solutions for problem instances containing up to sixty vessels. To the best of our knowledge, these are the largest instances solved to optimality in the literature, which makes our work applicable for the solution of real-life problems.

The next section is devoted to the formulations of the new models. We present the new necessary and sufficient condition for generating a regular work plan from an optimal solution of BACAP and propose a simple post-processing procedure in Section 3. In Section 4 we present the new cutting plane algorithm that gives the optimal solution of BACASP. Section 5 reports the results of the computational study we perform with the new formulations, post-processing procedure and the new cutting plane algorithm. Finally, concluding remarks are given in Section 6.

2. Model formulation

Before describing our mathematical formulations for BACAP and BACASP, we will first discuss the underlying assumptions of our models, which are given as follows:

1. The planning horizon is divided into equal-sized time periods.
2. Crane relocation time is negligible since the length of each time period is much larger than the crane relocation time.
3. The berth is divided into equal-sized berth sections.
4. Each berth section is occupied by no more than one vessel in each time period.
5. Each quay crane can be assigned to at most one vessel per time period.
6. Each vessel has a minimum and maximum number of quay cranes that can be assigned to it.
7. The service of a vessel by quay cranes begins upon that vessel's berthing at the terminal, and it is not disrupted until the vessel departs.
8. The number of quay cranes assigned to a vessel does not change during its stay at the berth, which is referred to as a time-invariant assignment (Bierwirth & Meisel, 2010). Furthermore, the set of specific cranes assigned to a vessel is kept the same.

Assumptions 1–7 are quite common in the literature as far as BAP and BASP problems are considered. There are different assumptions, however, regarding the number of cranes assigned to a vessel during the time the vessel is at the berth. Some authors assume that the number of cranes may change dynamically between the minimum and maximum number of cranes (see, e.g. Park & Kim (2003), Meisel & Bierwirth (2009b)), and some others allow a limited number of changes (Zhang et al., 2010). There are also approaches as the one by Giallombardo et al. (2010), which can be seen as a compromise between these two modeling assumptions, where the authors introduce quay crane assignment profiles that represent the number of cranes available to a vessel