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Innovative Applications of O.R.

Optimal berth allocation, time-variant quay crane assignment and scheduling with crane setups in container terminals[☆]

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ABSTRACT

There has been a dramatic increase in world's container traffic during the last thirty years. As a consequence, the efficient management of container terminals has become a crucial issue. In this work we concentrate on the integrated seaside operations, namely the integration of berth allocation, quay crane assignment and quay crane scheduling problems. First, we formulate a mixed-integer linear program whose exact solution gives optimal berthing positions and berthing times of the vessels, along with their crane schedules during their stay at the quay. Then, we propose an efficient cutting plane algorithm based on a decomposition scheme. Our approach deals with berthing positions of the vessels and their assigned number of cranes in each time period in a master problem, and seeks the corresponding optimal crane schedule by solving a subproblem. We prove that the crane scheduling subproblem is NP-complete under general cost settings, but can be solved in polynomial time for certain special cases. Our computational study shows that our new formulation and proposed solution method yield optimal solutions for realistic-sized instances.

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1. Introduction

Shorter transit times, lower shipping costs, higher reliability and security, and multi-modality are some of the factors that make containers an attractive means of transportation. There has been a considerable growth in the share of containerized trade in the world's total dry cargo during the last 30 years: the increase between 2000 and 2010 was 53.3 percent, 11 percent of which is attributed to year 2010 alone (UNCTAD, 2011). As a consequence of such a drastic increase in container traffic, the efficient management of container terminals has become a crucial issue and attracted a considerable research effort from various disciplines, including Operational Research (Stahlbock & Voß, 2008; Steenken, Voß, & Stahlbock, 2004). This is a difficult task since there is a myriad of interdependent operations, which can be grouped as the seaside, transfer and yard operations (Vis & de Koster, 2003). In this work, we concentrate on the integrated planning of seaside operations, which includes the berth allocation problem (BAP), quay crane assignment problem (CAP) and quay crane scheduling problem (CSP). We direct any reader having a particular interest in the transfer and yard operations, especially in the transshipment flow of containers and the associated decision problems between the seaside and the yard, to the work by Vacca (2010).

Efficient planning of seaside operations has a direct impact on the dwell time of the vessels (i.e., the period elapsing between the arrival and departure times of the vessels, consisting of the sum of the waiting and processing times), which is one of the main performance measures at a container terminal. Major international maritime ports have several container terminals operated by different companies. Thus, longer dwell times can have a negative impact on the competitiveness of both the port and companies operating terminals there. This explains the existence of studies in the literature that are concerned with BAP, CAP, CSP, and their integrated versions; namely berth allocation and quay crane assignment problem (BACAP), crane assignment and scheduling problem (CASP) and berth allocation, quay crane assignment and scheduling problem (BACASP). The type of integration we aim for here is the so-called deep integration defined by Geoffrion (1994), where subproblems are combined in the form of a single, unified mathematical optimization framework.

Generally, BAP deals with the determination of optimal berthing times and positions of vessels in container terminals. The focus of CSP, on the other hand, is mainly in determining an optimal

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handling schedule of vessels for available cranes at the terminal. Excellent recent surveys of the related works with a classification according to some specific attributes are provided in Bierwirth and Meisel (2010, 2015), and Carlo, Vis, and Roodbergen (2015). CAP finds the optimal number of cranes assigned to the vessels, and thus can be seen as a special form of the optimal crane splitting problem (Steenken et al., 2004). CAP is relatively simpler and can easily be solved in practice to optimality using intuitive reasoning, which makes it a less attractive research problem. However, as can be realized, crane numbers have a direct effect on the processing times of the vessels. As a result, related decisions should be embedded within either BAP or CSP models.

To the best of our knowledge, the earliest attempts to study BACASP, namely the integration of BAP, CAP and CSP within a unified mathematical optimization model to determine optimal berthing times and positions of the vessels along with the number of cranes and their identities as well as schedules are due to Rashidi (2006), Theofanis, Golias, and Boile (2007), and Zhang, Zheng, Zhang, Shi, and Armstrong (2010). The integration is slightly weaker on the BAP side in the work by Liu, Wan, and Wang (2006). Their BACAP model determines both the optimal crane numbers and specifications, but an optimal solution includes berthing times of the vessels without any information on their berthing positions. Besides, they generate possible handling times for each vessel and each assignable number of cranes as inputs to their BACASP model using a preprocessing scheme. 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 CASP model with BAP. However, Meisel (2009) and Meisel and Bierwirth (2013) functionally integrate BAP, CAP and CSP in three phases. 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 BACASP model calculates optimal berthing times, berth allocations and crane number assignments of the vessels, and crane schedules simultaneously for calculated crane assignments. In this formulation, berth allocation constraints are based on the relative positions of the vessels in time-space representation, crane scheduling allows crane shifting with no crossing and the objective minimizes the sum of the total dwell times of the vessels and penalty caused by the late vessels. As can be noticed, Ak (2008) with this objective intends to favor fast vessel throughput. While this objective attempts to treat different vessels fairly, the cost accrued due to the roaming cranes is not considered. Yang (2008) also proposes an MILP formulation that integrates BAP, CAP and CSP. In this formulation, crane shifting is allowed and the berth allocation constraints are based on assigning the rectangles of the time-space grid (i.e., position assignments) to the vessels and the total makespan is minimized as the objective. Unfortunately, the negative effect of crane reallocations is not considered since crane traveling cost is ignored. In addition, both models can be solved exactly only for small instances, and therefore the authors propose heuristics for the solution of their formulations.

Regarding the number and mobility of cranes assigned to the vessels, there are different assumptions made in the literature. Some authors assume that the number of cranes may change dynamically between the minimum and maximum number of cranes (see, e.g. Meisel & Bierwirth, 2009; Park & Kim, 2003). Zhang et al. (2010) criticize such models by noting that the number of quay cranes assigned to a vessel cannot be changed frequently in practice due to the significant setup effort and adjustment time needed for moving the quay cranes. They assume that the number of quay cranes assigned to each vessel can be changed only once before the vessel departs. This motivation for reducing large setup losses due to the reallocation of quay cranes leads Türkoğulları, Taşkın, Aras, and Altınel (2014) to formulate a time-invariant model where the same subset of quay cranes serves a vessel during its stay at the berth. They essentially adopt the position assignment settings given in Ak (2008), where he considers continuous quay layout discretized by means of fixed length sections (for modeling purposes) and dynamic arrivals with time discretized by means of fixed length unit periods. In other words, in the position assignment formulation the time-space area is divided into unit rectangles having one berth section as height and one time period as length, which reduces BAP to the positioning of a certain number of small rectangles within a large rectangle without overlap. Here, each small rectangle represents a vessel whose height equals to its length measured in the number of berth sections and width equals to its berthing time measured in the number of periods as illustrated by Ak (2008), and Bierwirth and Meisel (2010). Türkoğulları et al. (2014) first provide a new position assignment formulation for time-invariant BACAP minimizing the total cost consisting of the sum of the cost of berthing away from the desired berth section, the cost of late berthing, the cost of late departures and the cost due to the change in the number of active cranes. Then, they propose an efficient cutting plane algorithm that benefits from an optimal solution of their BACAP formulation for exactly solving large BACASP instances. Although this is a very efficient method that can solve realistic instances, the crane assignments are time-invariant (Bierwirth & Meisel, 2010). This means that the group of cranes and their number assigned to a vessel remains the same during its stay at the berth. In Türkoğulları, Taşkın, Aras, and Altınel (2012) the authors relax time-invariance assumption and develop an MILP model that considers a time-variant version of the same problem and incorporate the cost due to the change in the number of assigned cranes. It is also a position assignment formulation minimizing the total cost but includes the flexibility that the number of active cranes may change dynamically. However, this approach is still restricted since the setup cost is not considered as realistically as possible and it is assumed that total setup cost is proportional to the number of setups. In other words, the total setup cost term in the objective function is based primarily on the frequency that the number of active cranes changes and does not pay attention to issues such as traveling time and traveling distance of the cranes. Similar issues arise for the integrated formulations of Ak (2008) and Yang (2008); they both consider time-variant crane assignments but do not take into account additional complications due to crane relocations and the resulting cost figures.

In this work, we follow this line of research and introduce a formulation that deeply integrates BAP, CAP, and CSP (BACASP), as our first major contribution. Our formulation allows the inclusion of realistic costs associated with crane relocations consisting of both variable and fixed costs. We remark that CSP considered here as a part of BACASP is similar to bus/train scheduling with cranes corresponding to buses/trains and berthed vessels waiting for cranes replacing bus stops/train stations. Since there is a distribution of resources, namely cranes, over time, this is a scheduling problem as well. However, it is simpler than crane operations scheduling and thus named as CAP(specific) by Bierwirth and Meisel (2010). The crane operation scheduling is defined by Bierwirth and Meisel (2010, 2015) and Carlo et al. (2015) as the general task scheduling for cranes. As a result, BACASP may be seen as the deep integration of BAP, CAP and CSP (i.e. these three problems are addressed within a unified framework in the form of a mathematical optimization decomposition model), where CSP determines the crane-to-vessel assignments and specific time periods of these assignments when berthing times and locations of the vessels and the number of cranes allocated to vessels are given. We also point out that this definition of CSP has been used before in the literature (Ak, 2008; Imai, Chen, Nishimura, & Papadimitriou, 2008; Park & Kim, 2003; Yang, 2008). The formulation we present in the

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