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MIP approaches for the integrated berth allocation and quay crane assignment and scheduling problem

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ABSTRACT

In this paper we consider an integrated berth allocation and quay crane assignment and scheduling problem motivated by a real case where a heterogeneous set of cranes is considered. A first mathematical model based on the *relative position formulation* (RPF) for the berth allocation aspects is presented. Then, a new model is introduced to avoid the big-M constraints included in the RPF. This model results from a discretization of the time and space variables. For the new discretized model several enhancements, such as valid inequalities, are introduced. In order to derive good feasible solutions, a rolling horizon heuristic (RHH) is presented. A branch and cut approach that uses the enhanced discretized model and incorporates the upper bounds provided by the RHH solution is proposed. Computational tests are reported to show (i) the quality of the linear relaxation of the enhanced models; (ii) the effectiveness of the exact approach to solve to optimality a set of real instances; and (iii) the scalability of the RHH based on the enhanced mathematical model which is able to provide good feasible solutions for large size instances.

1. Introduction

Maritime transportation is a major mode of transportation. Around 80% of global trade by volume and over 70% of global trade by value are carried by sea and are handled by ports worldwide (U08, 2014). Port activities involve several interrelated decisions, as berth assignment of vessels, quay crane assignment and scheduling, cargo placement, etc. During peak periods of activity delays may occur leading to large waiting costs. The request for operational efficiency at ports has motivated the increase of research during the last decades on such optimization problems, which is even more visible during the last years with a rapid increase on the number of papers, some of them focused on real applications. For a recent survey see Bierwirth and Meisel (2015).

This paper considers an integrated berth allocation and quay crane assignment and scheduling problem occurring at a port whose main activities are related to short sea shipping operations. For a given time period, a sets of vessels is considered. For each vessel the arrival time and cargo quantity (to load or unload) are known. The objective is to manage the load and unload operations in order to minimize the total service completion time. These operations are performed with a set of cranes that transfer the cargo between the vessels and the storage area at the yard, as depicted in Fig. 1. This problem integrates two subproblems: the Berth Allocation Problem (BAP), which aims to assign arriving vessels to berthing positions, and the quay crane assignment and scheduling problem (QCASP) where cranes are assigned to vessels, and their operations are scheduled. The complete problem is known by the acronym BACASP (Turkogullari, Taskin, Aras, & Altinel, 2014). The storage management of the cargo at the yard is not considered here.

The cranes are mounted on rails. This physical limitation creates operational restrictions on the quay areas where each crane can operate, and enforces non-crossing constraints, that is, the relative position of the cranes cannot be exchanged, see Fig. 1. An additional complexity of this real problem is the existence of a heterogeneous set of cranes types, with different processing rates. The physical operational limitation of the cranes combined with the cranes efficiency, make some berthing areas more attractive than others. Typically an area that is served by a more efficient crane tends to be used more often than the other areas. Other physical aspects, such as the proximity to the storage yard, the structure of the berth, may also influence berth allocation. See for example Beens and Ursavas (2016). This fact makes the BACASP that results from the integration of both subproblems (BAP and QCASP) even

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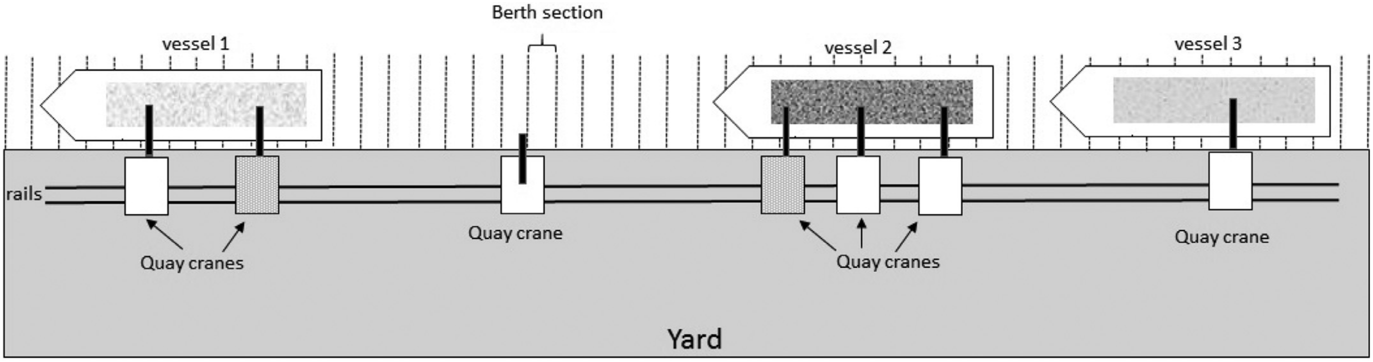

Fig. 1. Example of a quay operation on three ships and seven cranes (five of them of one type and the other two of other type), six of them operating.

more relevant than in the case of homogeneous cranes. Following the classical approach for BAP (see Guan & Cheung, 2004), a time and space discretization is assumed. The wharf is divided into sections of the same length. Contrary to the case of the discrete berth allocation, where each vessel is assigned to a single berth position, in the continuous berth allocation several adjacent sections are assigned to each vessel, corresponding to its length. The continuous berth allocation assumption is more flexible and such flexibility is required in practical cases, as the one we consider, where the wharf length is a binding restriction and the set of cranes is heterogeneous.

As BACASP has many variants which depend on the assumptions made, next we list the assumptions for our problem:

1. A dynamic berth allocation where vessels are allowed to arrive any time within the planning horizon but their arriving time is deterministic.
2. No service priorities are considered.
3. Vessels are allowed to moor at any place along the wharf, which is known in the literature as the continuous berth allocation.
4. The berth is divided into berth sections of equal length.
5. The time horizon is divided into time periods of equal length.
6. A time-variant assignment of cranes, that is, a crane can be assigned to a vessel and move to another vessel in the following period while the first vessel is still operating.
7. Non-crossing constraints and safety space between cranes must be obeyed.

Both subproblems BAP and QCASP have received great attention in the past years, see the survey (Bierwirth & Meisel, 2010) and its follow-up (Bierwirth & Meisel, 2015) with a very recent overview and classification. As the integrated problem is very complex many approaches consider the two problems separately. For the BAP see, for instance, Guan and Cheung (2004), Imai, Nishimura, and Papadimitriou (2001), Imai, Sun, Nishimura, and Papadimitriou (2005), Lim (1998), Mauri, Ribeiro, Lorena, and Laporte (2016), Ursavas and Zhu (2016), Zhen (2015), Zhen, Lee, and Chew (2011). For the QCASP see Al-Dhaheri and Diabat (2015), Daganzo (1998), Diabat and Theodorou (2014), Guan, Yan, and Zhou (2010), Kim and Park (2004), Lim, Rodrigues, Xiao, and Zhu (2004), Liu, Wan, and Wang (2006), Moccia, Cordeau, Gaudioso, and Laporte (2006), Peterkofsky and Daganzo (1990), Sampaio, Urrutia, and Oppen (2016), Theodorou and Diabat (2015). Some authors consider the travelling times of cranes when moving between quay positions, see Kim and Park (2004), Moccia, Cordeau, Gaudioso, and Laporte (2006). Here we assume that such travelling times are negligible. Crane scheduling problems at port terminals may occur not only at the quay area but at other areas, such as the storage area. Although such storage management issues can be very complex, see for example Gharehgozli, Laporte, Yu, and de Koster (2015), Gharehgozli, Yu, Zhang, and de Koster (2017), here we consider only the scheduling of the quay cranes. For a recent classification of the crane scheduling problems see Boysen, Briskorn, and Meisel (2017).

It is well-known that better solutions can in general be obtained by analyzing all the decisions together. The integrated problem has been considered before in several papers such as Ak (2008), Blazewicz, Cheng, Machowiak, and Oguz (2011), Chang, Jiang, Yan, and He (2010), Chen, Lee, and Cao (2012), Han, Lu, and Xi (2010), Imai, Chen, Nishimura, and Papadimitriou (2008), Iris, Pacino, Ropke, and Larsen (2015), Giallombardo, Moccia, Salani, and Vacca (2010), Liang, Huang, and Yang (2009), Meisel and Bierwirth (2009), Park and Kim (2003), Raa, Dullaert, and Van Schaeren (2011), Song, Cherrett, and Guan (2012), Theodorou and Diabat (2015), Turkogullari, Taskin, Aras, and Altinel (2014), Vacca, Salani, and Bierlaire (2013), Zhang, Zheng, Zhang, Shi, and Armstrong (2010), Zampelli, Vergados, Van Schaeren, Dulleart, and Birger (2013), Yang, Wang, and Li (2012).

Next we briefly review some of the most relevant references for the integrated model. For a more detailed information on the problem characteristics and approaches we suggest the very recent work (Iris, Pacino, Ropke, & Larsen, 2015).

Park and Kim (2003) present an integer programming model which is used in a two-phases solution procedure. Ak (2008) provides both a mathematical analysis and heuristics. Chang, Jiang, Yan, and He (2010) focus on heuristic approaches: a rolling-horizon approach and a hybrid parallel genetic algorithm. Model formulations and genetic algorithms are also presented by Imai, Chen, Nishimura, and Papadimitriou (2008) and Liang, Huang, and Yang (2009). Meisel and Bierwirth (2009) give several heuristic procedures including a construction heuristic, local refinement procedures, and two meta-heuristics. Heuristic procedures are developed also by Zhang, Zheng, Zhang, Shi, and Armstrong (2010) (a subgradient based heuristic) and Yang, Wang, and Li (2012) (an evolutionary algorithm). Blazewicz, Cheng, Machowiak, and Oguz (2011) consider the integrated problem as a scheduling problem where tasks are considered the ships and processors are the quay cranes. Giallombardo, Moccia, Salani, and Vacca (2010) consider a MILP model to solve small instances and a Tabu search heuristic for generating feasible solutions. Raa, Dullaert, and Van Schaeren (2011) present a formulation that is used in a hybrid heuristic solution procedure. Song, Cherrett, and Guan (2012) follow a bi-level programming approach where the BAP is considered in the upper-level problem and the QCASP is considered in the lower-level. Recently a constraint programming approach was followed by Zampelli, Vergados, Van Schaeren, Dulleart, and Birger (2013). In a different perspective, Han, Lu, and Xi (2010) consider the case with uncertainty on the vessel arrival times. They propose a mixed