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A branch-and-price algorithm to solve the integrated berth allocation and yard assignment problem in bulk ports

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A B S T R A C T

In this research, two crucial optimization problems of berth allocation and yard assignment in the context of bulk ports are studied. We discuss how these problems are interrelated and can be combined and solved as a single large scale optimization problem. More importantly we highlight the differences in operations between bulk ports and container terminals which highlights the need to devise specific solutions for bulk ports. The objective is to minimize the total service time of vessels berthing at the port. We propose an exact solution algorithm based on a branch and price framework to solve the integrated problem. In the proposed model, the master problem is formulated as a set-partitioning problem, and subproblems to identify columns with negative reduced costs are solved using mixed integer programming. To obtain sub-optimal solutions quickly, a metaheuristic approach based on critical-shaking neighborhood search is presented. The proposed algorithms are tested and validated through numerical experiments based on instances inspired from real bulk port data. The results indicate that the algorithms can be successfully used to solve instances containing up to 40 vessels within reasonable computational time.

1. Introduction

Maritime transportation is a major channel of international trade. In the last decade, the shipping tonnage for dry bulk and liquid bulk cargo has risen by 52% and 48% respectively. The total volume of dry bulk cargoes loaded in 2008 stood at 5.4 billion tons, accounting for 66.3% of total world goods loaded UNCTAD (2009). The proper planning and management of port operations in view of the ever growing demand represents a big challenge. A bulk port terminal is a zone of the port where sea-freight docks on a berth and is stored in a buffer area called yard for loading, unloading or transshipment of cargo. In general, the bulk terminal managers are faced with the challenge of maximizing efficiency both along the quay side and the yard. From the past research, it is well established that operations research methods and techniques can be successfully used to optimize port operations and enhance terminal efficiency. However while significant contributions have been made in the field of large scale optimization for container terminals, relatively little attention has been directed to bulk port operations.

Bulk terminal operations planning can be divided into two decision levels depending on the time frame of decisions: tactical level and operational level. Tactical level decisions involve medium to short term decisions regarding resource allocation such as port equipment and labor, berth and yard management, and storage policies. In practice, these decisions could be based on "rules of thumb" in which the experience of the port managers plays an important role, or alternatively more scientific approaches based on operations research methods could be in use. The operational level involves making daily and real time decisions such as crane scheduling, yard equipment deployment and last minute changes in response to disruptions in the existing schedule. This paper focuses on the tactical level decision planning for the integrated berth and yard management in the context of bulk ports. We focus in particular on two crucial optimization problems in the context of bulk port terminals: The Berth Allocation Problem (BAP) and the yard assignment problem.

The tactical berth allocation problem refers to the problem of assigning a set of vessels to a given berthing layout within a given time horizon. There could be several objectives such as the minimization of the service times of vessels, the minimization of the port stay time, the minimization of the number of rejected vessels, and the minimization of the deviation between actual and planned berthing schedules. There are several spatial and temporal constraints involved in the BAP, which lead to a multitude of BAP

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formulations. The temporal attributes include the vessel arrival process, the start of service, the handling times of vessels, while the spatial attributes relate to the berth layout, the draft restrictions and others. In a container terminal, all cargo is packed into containers, and thus there is no need for any specialized equipment to handle any particular type of cargo. In contrast, in bulk ports, depending on the vessel requirements and cargo properties, a wide variety of equipment is used for discharging or loading operations. Thus, the cargo type on the vessel needs to be explicitly taken into consideration while modeling the berth allocation problem in bulk ports. The tactical yard assignment problem refers to decisions that concern the storage location and the routing of materials. This affects the travel distance between the assigned berth to the vessel and storage location of the cargo type of the vessel on the yard, and furthermore determines the storage efficiency of the yard. Thus, the problems of berth allocation and yard management are interrelated. The start and end times of vessel operations determine the workload distribution and the deployment of yard equipment such as loading shovels and wheel loaders in the yard side. Moreover, berthing locations of vessels determine the storage locations of specific cargo types to specific yard locations, which minimize the total travel distance between the assigned berthing positions to the vessels and the yard locations storing the cargo type for the vessel. Similarly, the yard assignment of specific cargo types has an impact on the best berthing assignment for vessels berthing at the port. In this study, we present an integrated model for the dynamic, integrated berth allocation problem and yard assignment in the context of bulk ports. Few scholars have investigated this problem in the context of container terminals, and there is no published literature for bulk ports. We present an exact solution algorithm based on branch-and-price and a metaheuristic approach based on critical-shaking neighborhood search to solve the combined large scale problem. Numerical experiments based on real-life-inspired port data indicate that the proposed algorithms can be successfully used to solve even large instances.

2. Literature review

From the past OR literature on container terminal operations, it is well established that integrated planning of operations can allow port terminals to reduce congestion, lower delay costs and enhance efficiency. Significant contribution has been made in the field of large scale optimization and integrated planning of operations in container terminals. Bulk ports on the other hand have received almost no attention in the operations research literature. The integrated berth allocation and quay crane assignment or scheduling problem has been studied in the past by Park and Kim (2003), Meisel and Bierwirth (2006), Imai, Chen, Nishimura, and Papadimitriou (2008), Meisel and Bierwirth (2009), and more recently by Giallombardo, Moccia, Salani, and Vacca (2010) and Vacca (2011) for container terminals. Comprehensive literature surveys on container terminal operations can be found in Steenken, Voss, and Stahlbock (2004), Stahlbock and Voss (2008), and Bierwirth and Meisel (2010).

The dynamic, hybrid berth allocation problem in the context of bulk ports is studied by Umang, Bierlaire, and Vacca (2013). The berth allocation problem in container terminals has been widely studied in the past. Imai, Nagaiwa, and Chan (1997), Imai, Nishimura, and Papadimitriou (2001, 2003, 2008), Monaco and Sammarra (2007), Buhrkal, Zuglian, Ropke, Larsen, and Lusby (2011), Zhou and Kang (2008), Han, Lu, and Xi (2010), Cordeau, Laporte, Legato, and Moccia (2005), Mauri, Oliveira, and Lorena (2008) propose methods to solve the discrete berth allocation problem. The continuous berth allocation problem is studied by Li, Cai, and Lee (1998), Guan, Xiao, Cheung, and Li (2002), Park and Kim (2003), Guan and Cheung (2004), Park and Kim (2002), Kim and Moon (2003), Lim (1998), Tong, Lau, and Lim (1999), Imai, Sun, Nishimura, and Papadimitriou (2005) and Chang, Yan, Chen, and Jiang (2008). The berth allocation problem with hybrid layout is addressed by Moorthy and Teo (2006), Dai, Lin, Moorthy, and Teo (2008), Nishimura, Imai, and Papadimitriou (2001) and Cheong, Tan, Liu, and Lin (2010), and position-dependent handling times are considered by Cordeau et al. (2005) and Imai, Nishimura, Hattori, and Papadimitriou (2007) for indented berths.

Yard management in container terminals involves several tactical and operational level decision problems. Scheduling and deployment of yard cranes is addressed by Cheung, Li, and Lin (2002), Zhang, Wan, Liu, and Linn (2002), Ng and Mak (2005), Ng (2005) and Jung and Kim (2006). Storage and space allocation, stacking and re-marshalling strategies have been studied by Kim and Kim (1999), Kim, Lee, and Hwang (2003), Lee, Chew, Tan, and Han (2006) and few others. Nishimura, Imai, and Papadimitriou (2009) investigate the storage plan for transshipment hubs, and propose an optimization model to minimize the sum of the waiting time of feeders and the handling times for transshipment containers flow. Transfer operations that consist of routing and scheduling of internal trucks, straddle carriers and AGV's have been studied by Liu, Jula, Vukadinovic, and Ioannou (2004), Vis, de Koster, and Savelsbergh (2005), and Cheng, Sen, Natarajan, Teo, and Tan (2005) among others. Works on integrated problems related to yard management in container terminals include Bish, Leong, Li, Ng, and Simchi-Levi (2001) and Kozan and Preston (2006) who propose the integration of yard allocation and container transfers, whereas Chen, Lei, and Zhong (2007) and Lau and Zhao (2007) study the integrated scheduling of handling equipment in a container terminal. In the following, we discuss in more detail some articles relevant to our study.

Moorthy and Teo (2006) discuss the concepts of berth template and yard template in the context of transshipment hubs in container shipping. They study the delicate trade-off between the level of service as indicated by the vessel waiting times and the operational cost for moving containers between the yard and quay in a container terminal. A robust berth allocation plan is developed using the sequence pair approach, with the objective to minimize the total expected delays and connectivity cost that is related to the distance between the berthing positions of vessels belonging to the same transshipment group.

Cordeau, Gaudioso, Laporte, and Moccia (2007) study the Service Allocation Problem (SAP), a tactical problem arising in the yard management of Gioia Tauro Terminal. The SAP is a yard management problem that deals with dedicating specific areas of the yard and the quay to the services or route plans of shipping companies which are planned in order to match the demand for freight transportation. The objective of the SAP is the minimization of container rehandling operations in the yard and it is formulated as a Generalized Quadratic Assignment Problem (GQAP, see e.g. Cordeau, Gaudioso, Laporte, & Moccia (2006) and Hahn, Kim, Guignard, Smith, & Zhu (2008)). An evolutionary heuristic is developed to solve larger instances obtained from the real port data.

Zhen, Chew, and Lee (2011) propose a mixed integer model to simultaneously solve the tactical berth template and yard template planning in transshipment hubs. The objective is to minimize the sum of service cost derived from the violation of the vessels expected turnaround time intervals and the operation cost related to the route length of transshipment container flows in the yard. A heuristic algorithm is developed to solve large scale instances within reasonable time and numerical experiments are conducted on instances from real world data to validate the efficiency of the proposed algorithm.