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A network flow model for the dynamic and flexible berth allocation problem

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ABSTRACT

This paper presents a new model for the dynamic berth allocation problem (BAP). The model is developed using a berth-flow network modeling approach and is formulated as an integer multi-commodity network flow problem. In addition, an innovative flexible berth-space utilization scheme, based on blocking plans, is incorporated into the proposed model. This is referred to as the dynamic (vessel arrivals) and flexible (berth space) BAP model (or DFBAP), and is designed to better utilize wharf space in a container port. Computational experiments conducted on an instance generated using actual data show that the DFBAP model is more effective and efficient than the method currently used by port authorities. A set of scenario analyses is also performed to obtain insights into important model parameters.

1. Introduction

Seaports are the interface between sea and land transportation. They are the terminals where shipping containers move from one mode of transportation to another, from sea to land (road or rail) and vice versa, or from one vessel to another as part of a hub-and-spoke maritime network. Due to the steady increase in the use of shipping containers for global cargo transportation, port authorities are now facing serious challenges in port management, which involves a series of operational decisions for efficiently processing containers in the berth (where containers are loaded and unloaded) and the stowage areas (where containers are stored). Among terminal operations, an effective scheme for berth allocation is critical to the efficient management of container flow. Berth space is often very limited at most seaports and the construction cost of berths is relatively high compared to the investment in other facilities at a port.

This research deals with the berth allocation problem (BAP) in a multi-user or public container terminal. The BAP entails determining optimal berthing times and positions for a collection of ships, while satisfying a number of spatial and temporal operational constraints. The productivity of a container terminal depends greatly on the efficient berth assignment of incoming ships, and hence the BAP has long been recognized as one of the major container terminal optimization problems discussed in the literature.

In previous studies, the BAP could be either static (SBAP) or dynamic (DBAP) (Imai, Nagaiwa, & Tat, 1997; Imai, Nishimura, & Papadimitriou, 2001). The SBAP assumes all ships to have already arrived at the port when the allocation process begins, whereas the DBAP considers not only ships that have already arrived but also those that will arrive within the planning horizon. This research focuses on the DBAP. Additionally, depending on the construction (or configuration) of the wharf, the berths can be classified either as discrete or continuous (e.g., Cordeau, Laporte, Legato, & Moccia, 2005; Imai, Sun, Nishimura, & Papadimitriou, 2005; Karafa, Golias, Ivey, Saharids, & Leonardos, 2013; Lin & Ting, 2014). In the discrete case, the wharf is partitioned into several berths. A vessel cannot moor across a berth boundary and multiple vessels cannot occupy the same berth at the same time. This type of DBAP is referred to as the discrete DBAP (DDBAP) in this paper. Numerous past works had devoted to the DDBAP and its variants (e.g., Brown, Lawphongpanich, & Thurman, 1994; Buhrkal, Zuglian, Ropke, Larsen, & Lusby, 2011; Imai, Nishimura, Hattori, & Papadimitriou, 2007; Imai, Nishimura, & Papadimitriou, 2003; Imai et al., 2001; Monaco & Samara, 2007; Nishimura, Imai, & Papadimitriou, 2001). On the other hand, in the continuous DBAP (DCBAP), the wharf is represented as a continuous line and vessels are allowed to moor at any place along the wharf (e.g., Arango, Cortes, Onieva, & Escudero, 2013; Cheong, Lin, Tan, & Liu, 2007; Kim & Moon, 2003; Lee & Chen, 2009; Lee, Chen, & Cao, 2010; Park & Kim, 2003; Wang & Lim, 2007; Xu, Chen, & Quan, 2012). The development of the DCBAP is motivated by the great diversity in vessel lengths, the implication

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being that the discrete berth allocation method cannot make full use of the terminal berth resources. The DDBAP assumes a finite set of berthing points or discrete berthing locations, which may decrease the utilization efficiency of wharf resources. Although the DCBAP provides more flexibility and efficiency for berth allocation, it also significantly increases the complexity of the problem, making it much more difficult to solve.

Recognizing that both the DDBAP and the DCBAP have their pros and cons, this research proposes a flexible scheme for the DBAP based on a set of predetermined blocks. Hereafter, the new DBAP problem, introduced in this paper, is referred to as the dynamic (vessel arrivals) and flexible (berth space) BAP (or DFBAP). The set of blocks determines a number of blocking plans, where each blocking plan consists of multiple berths with different sizes (or lengths) for servicing the vessels. Using the blocking plans make the DFBAP more flexible and effective than the conventional DDBAP, because the DDBAP is a special case of the DFBAP with only one blocking plan. The DFBAP works by using a finite set of (discrete) blocks to form the blocking plans. In the DCBAP, on the other hand, the wharf is represented as a continuous line and vessels can berth anywhere along the wharf, meaning that the wharf can be viewed as consisting of an infinite number of blocks. Essentially, the set of blocks used in the DFBAP model can be considered as an approximation to the infinite number of blocks in the DCBAP model. If one can identify a complete set of blocks such that all possible blocking plans have been considered (i.e., a close approximation to the infinite number of blocks in the DCBAP model), then the solution of the DFBAP is close to that of the DCBAP.

The DFBAP model is developed using a time–space network flow approach. Similar approaches have been successfully adopted in previous studies for the formulation of conveyance movements in the dimensions of time and space (e.g., Yan & Chen, 2011; Yan, Chen, & Lin, 2009; Yan & Tang, 2007). The DFBAP is formulated as an integer multiple commodity network flow problem and can be solved by using commercial mathematical programming software, such as CPLEX. The performance of the DFBAP model is evaluated using a real problem instance generated based on the actual data from a major container port in Taiwan. A set of scenario/sensitivity analyses is also conducted to examine the properties of the proposed model.

This paper contributes significantly to the existing DBAP literature as follows: first, the berth-flow network modeling approach provides an effective way of solving this complex problem; second, the flexible berth allocation scheme based on the blocking plans increases berth space utilization in a wharf; third, the cost scheme designed in the berth-flow networks prioritizes the assignment of vessels to their compatible types of berth and avoids the violation of the first-come-first-serve (FCFS) rule commonly adopted in practice. To the best of the authors' knowledge, none of the previous studies was able to provide these rich modeling capabilities simultaneously in an integrated framework.

The rest of this paper is organized as follows. The problem and assumptions are described in Section 2. The design of the berth-flow network is introduced in Section 3, followed by the description of the network flow-based DFBAP model in Section 4. Section 5 presents the numerical example and results. Concluding remarks are given in Section 6.

2. Problem description

The DFBAP addressed in this research can be described in a two dimensional space, where the spatial dimension denotes the quay length and the temporal dimension represents the planning horizon. Given a collection of vessels that are to arrive at the port within the planning horizon, the problem aims to determine the berthing time and location for each of the vessels. Each vessel will come into the port, wait for the scheduled berthing time, berth at the designated position within the allocated berth, load/unload containers, and then leave the port. The assumptions made for the DFBAP are illustrated as follows:

1. Every vessel must be serviced exactly once at one of the available berths determined in the blocking plan.
2. Every berth can service only one vessel at one time.
3. The configurations and locations of the berths in the wharf are known, a priori.
4. The types (or sizes), arrival/departure times and handling times of the vessels arriving within the planning horizon are known in advance. The handling times (each including a short setup time) for a vessel could vary depending on the berth, due to the different physical configuration of the berths.
5. The physical configuration of a berth, including length and water-depth, must be suited to the vessel assigned to that berth.
6. The first-come-first-serve (FCFS) rule is adopted only for assigning vessels of the same type or similar types, and as a soft constraint that may be violated with a penalty. In practice, not every arriving vessel is assigned immediately after the terminal planner receives its call. Actually, the FCFS rule is typically adopted by the planner when assigning vessels with the same berthing conditions (e.g., berth length and water-depth). For example, if there is a small-size berth available, the planner will assign that berth to a small-size vessel that arrives later, rather than a large-sized vessel that arrives earlier.
7. In practice, some of the vessels are not immediately serviced or cannot be serviced within the planning horizon when they enter a port, due to insufficient berth space. Thus port authorities can employ a waiting (or delay) strategy that suitably delays some vessels such that more (or even all) vessels can be serviced given the limited berth space. This motivates us to include the total waiting time plus a penalty for being unable to service vessels within the planning horizon in the objective function of the DFBAP model.
8. To prevent long waiting times which would impact the level of service and cause severe delays to the vessels, a maximum waiting time (adjustable to meet the port authority's operational requirements), is set for each of the vessels.
9. There is a safety gap between consecutively-docked vessels. For instance, in our numerical example, the port authority requires the safety gap be at least 10 m. For simplicity, this research adds a safety gap to the vessel length and to the wharf length, which not only satisfies the port's regulations but also reduces the complexity of the model.
10. We address the DFBAP in a short-term planning horizon (or period). This assumption follows from the practical port operation adopted in some of the container terminals in Taiwan. For instance, the planning horizon is from 6 AM one day to 6 AM the next day in the container port in our case study. Note that if some of the berths are still occupied by some vessels (arriving at the last planning period) at the beginning of the current planning period, those berths will be considered as unavailable until those vessels leave. The proposed model is executed for every planning period with updated information. In addition, the planning period can be extended to be several days or a week, if the vessel and berth data are available for the entire planning period. A rolling analysis could be applied for a long planning period.

Given the above assumptions, the objective of the DFBAP is to minimize the total waiting time and the penalties for being unable