European Journal of Operational Research 000 (2018) 1–13

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

The berth allocation problem in terminals with irregular layouts

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A R T I C L E I N F O

Article history:
Received 24 February 2018
Accepted 8 July 2018
Available online xxx

Keywords:
Combinatorial optimization
Port terminal
Berth allocation
Integer programming
Iterated local search

A B S T R A C T

As international trade thrives, terminals attempt to obtain higher revenue while coping with an increased complexity with regard to terminal management operations. One of the most prevalent problems such terminals face is the Berth Allocation Problem (BAP), which concerns allocating vessels to a set of berths and time slots while simultaneously minimizing objectives such as total stay time or total assignment cost. Complex layouts of real terminals introduce spatial constraints which limit the mooring and departure of vessels. Although significant research has been conducted regarding the BAP, these real-world restrictions have not been taken into account in a general way. The present work proposes both a mixed integer linear programming formulation and a heuristic, which are capable of obtaining optimal or near-optimal solutions to this novel variant of the BAP. In order to assess the quality of the heuristic, which is being employed in a real tank terminal in Belgium, it is compared against the exact approach by way of randomly-generated instances and real-world benchmark sets derived from the tank terminal.

1. Introduction

Ships have increasingly become an essential component within international trade. Every day cargo ships leave from and dock at port terminals, thereby providing consumers with a wide variety of goods. The development of naval engineering, the extension of container-based transport and the enhancement of bulk facilities now make it possible to carry huge quantities of resources from one side of the world to the other in very short time. This places pressure on port terminals, which compete against each other to offer the best service to customers primarily by seeking the shortest ship waiting times.

One of the most critical problems that terminals face when optimizing their operations is the Berth Allocation Problem (BAP). This problem concerns assigning a specific berth and a time slot to each vessel, while minimizing the total cost or service time. The berth characteristics, vessel dimensions and estimated arrival and departure times restrict the number of compatible berths for each vessel.

The BAP has been studied considering different characteristics and operational aspects. The surveys of seaside operations at container terminals published by Bierwirth and Meisel (2010, 2015) present the main variants addressed by academic researchers. In literature work, a classification is usually formed by considering temporal and spatial attributes. The temporal attribute describes the arrival process of vessels. According to Imai, Nishimura, and Papadimitriou (2001), *static* and *dynamic* temporal assumptions may restrict berthing times. The *static* variant occurs when ships arrive prior to berth allocation; it is assumed that vessels are already waiting in the port and can therefore berth immediately. By contrast, the *dynamic* case assumes that arrival times are provided for all vessels, meaning that mooring is only possible from a vessel's arrival. The existing temporal classification was extended by Bierwirth and Meisel (2015) with *cyclic* and *stochastic* because of their occurrence in recent papers. The cyclic variant assumes that vessels arrive at terminals according to a fixed liner schedule. Finally, stochastic arrival times are determined by either a certain random distribution or by real-life scenarios. Note that it is crucial to highlight how 'dynamic' in the context of established literature concerning the BAP has an entirely different meaning when compared against what it denotes throughout the operational research community more generally. Specifically, the dynamic BAP refers to the case where unique arrival times for vessels are known in advance rather than symbolising any change or response to new data.

With respect to the spatial attribute, the BAP may be classified as *discrete*, *continuous* or *hybrid* depending on the berthing layout.

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https://doi.org/10.1016/j.ejor.2018.07.019
0377-2217/

Please cite this article as: J.F. Correcher et al., The berth allocation problem in terminals with irregular layouts, European Journal of Operational Research (2018), https://doi.org/10.1016/j.ejor.2018.07.019

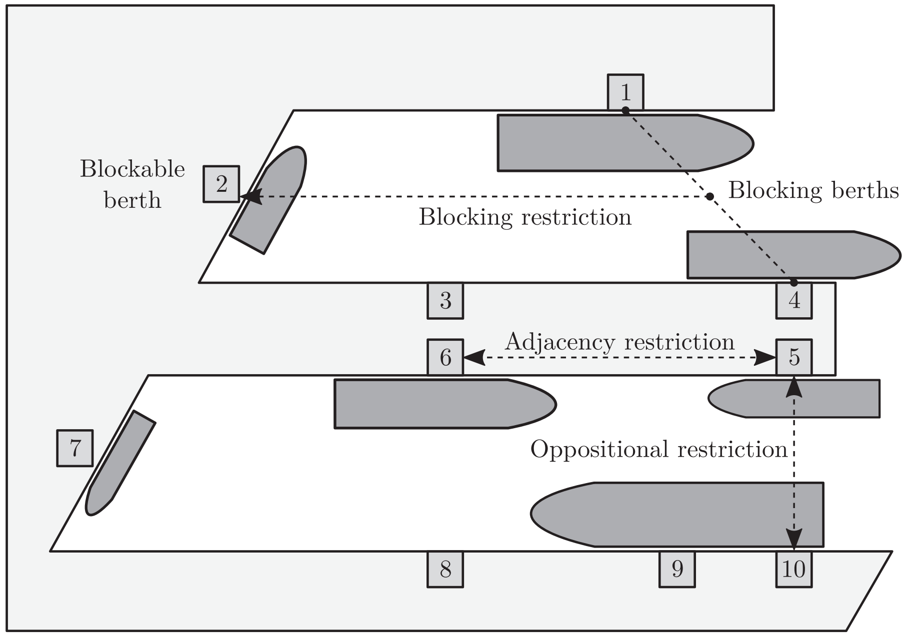

Fig. 1. Terminal with irregular layout. Only some of the occurring spatial restrictions are shown.

The *discrete* variant considers the quay as consisting of a finite set of berths or sections such that only one ship may be moored and served at each berth at any one time. In the *continuous* version, no quay partitioning exists and therefore vessels may berth at arbitrary positions within the boundaries of the quay. Finally, the *hybrid* variant considers the quay to be partitioned into a number of berths, with vessels capable of sharing a berth or occupying more than one under certain conditions.

Beyond these aspects, the geometrical disposition of the berths along the quay and the resulting operational implications have rarely been considered up to date. Important problems posed by irregular terminal layouts in which berths are adjacent or opposite to each other have thus remained unaddressed. This is often the case in terminals located at highly developed ports wherein artificial docks form indented quays. For example, in terminals such as the one depicted in Fig. 1, distances between berths together with their concurrent usage prevent vessels from docking at or departing from some berths subject to given rules. This also gives rise to special restrictions between berths which form virtual gates and thus may block the access to inner berths.

The present work addresses the discrete and dynamic BAP for the general case of terminals with irregular layouts involving adjacency, oppositional and blocking restrictions between berths. Permitted berthing operations are addressed by formulating them in a general fashion, thereby enabling both representing and solving the problem in wide variety of terminal layouts.

An original exact approach based on a Mixed Integer Linear Programming (MILP) model is proposed for solving small instances and a heuristic approach based on Iterated Local Search (ILS) and Ruin & Recreate strategies is proposed for larger ones. The heuristic approach is currently being used as a decision support tool for generating feasible schedules in a tank terminal with an irregular layout.

The remainder of this paper is structured as follows. Section 2 presents a literature review aimed towards highlighting the main academic contributions and related work. Next, the problem is formally introduced and defined (Section 3). In Section 4 an MILP model for the problem is proposed, while a heuristic approach is described throughout Section 5. Computational experiments and results are discussed in Section 6. Finally, Section 7 presents conclusions and future lines of research which may result from this work.

2. Literature review

Berth allocation was first studied as an optimization problem in the late 1990s. The static variant of the discrete BAP was first formulated by Imai, Nagaiwa, and Tat (1997), while the dynamic variant was addressed by Imai et al. (2001) and Hansen and Oğuz (2003). Regarding the continuous version, the static and dynamic variants were first formulated by Li, Cai, and Lee (1998) and Lim (1998), respectively. Since then, the BAP has attracted ever-increasing attention in the combinatorial optimization community, and many new variants and characteristics of this problem have been addressed. The most recent reviews of the academic literature regarding seaside operations, including the BAP, were published by Bierwirth and Meisel (2010, 2015) and Carlo, Vis, and Roodbergen (2015). In recent years, researchers have proposed new solution methods for addressing the BAP which respect more realistic conditions and characteristics (Table 1).

Academic work has primarily focused on terminals consisting of linear quays where the berthing of vessels is only restricted by the berths' spatial compatibility and their temporal occupation. Adjacency, oppositional and blocking restrictions between berths have rarely been considered and those studies which did address these restrictions were limited to specific terminal layouts.

Consider, for example, Imai, Nishimura, Hattori, and Papadimitriou (2007), who tackled a discrete BAP in which a dedicated indented berth is capable of serving either one mega-containership or up to four small vessels. This indented berth, located in the port of Amsterdam, has cranes located on both opposite quays, thereby enabling larger vessels to be served faster than at an ordinary berth. When there are no such large vessels in the port, terminal operators use this berth to serve smaller vessels. In the specific case addressed by Imai et al. (2007), two small vessels are capable of docking either side of the berth if their combined lengths do not exceed the total length of the indented berth. This introduced the problem of accessing or leaving the inner sections of the berth when the outer sections were occupied by other vessels. The berth planner consequently had to take into account the