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DOI
10.1007/978-3-031-16579-5_1

Publication date
2022

Document Version
Final published version

Published in
Computational Logistics -

Citation (APA)
Lyu, X., & Schulte, F. (2022). Hybrid Berth Allocation for Bulk Ports with Unavailability and Stock Level Constraints. In J. de Armas, H. Ramalhinho, & S. Voß (Eds.), *Computational Logistics - : Proceedings of the 13th International Conference, ICCL 2022* (pp. 3-15). (Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Vol. 13557 LNCS). Springer. https://doi.org/10.1007/978-3-031-16579-5_1

Hybrid Berth Allocation for Bulk Ports with Unavailability and Stock Level Constraints

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Abstract. Berth allocation is fundamental to port-related operations in maritime shipping. Port managers have to deal with the increasing demands either by expanding the terminals or by improving efficiency to maintain competitiveness. Port expansion is a long-term project, and it requires much capital investment. Thus, the question of how to enhance the efficiency of berth allocation has received much research interest. Research on the Berth Allocation Problem (BAP) in container ports is quite advanced. However, only limited research focuses on BAP in bulk ports, although some similarities exist. Contributing to Operations Research approaches on the BAP, this paper develops a hybrid BAP mixed-integer optimization model dedicated to bulk ports. In addition to considering the handling characteristics of bulk ports, we also incorporate more practical factors such as unavailability and stock levels. The objective of the proposed model is to minimize the demurrage fee for all vessels under consideration of unavailability and stock constraints. We use the commercial software CPLEX to obtain the optimal solutions for a set of distinct instances, explicitly considering the situation of multiple cargo types on one vessel, which provides a better fit for the loading or discharging operations in real-world bulk ports. This is the first study to our knowledge that dedicates itself to the BAP in bulk ports and considers unavailability and stock constraints simultaneously. Our solutions can provide timely and effective decision support to bulk port managers.

Keywords: Berth Allocation Problem · Bulk ports · Unavailability · Stock levels · Optimization · Mixed-integer program

1 Introduction

Over the past decades, the tonnage of bulk cargo carried by sea shipping has increased sharply. Based on [21], in 2020, the international dry bulk trade and tanker trade was 8.085 billion tons, accounting for 75.9% of the world's total

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Supported by the scholarship from China Scholarship Council (CSC) under the Grant CSC 202107720039.

J. de Armas et al. (Eds.): ICCL 2022, LNCS 13557, pp. 3–15, 2022.
https://doi.org/10.1007/978-3-031-16579-5_1

cargo load. The ever-growing demand makes efficient loading or discharging of vessels a great challenge, and it has generated many research interests recently. Generally, the Berth Allocation Problem (BAP) is concerned with the optimal decisions on assigning a berthing position and berthing time to the calling vessels. Operation Research (OR) methods and techniques contribute significantly to the BAP in container ports and provide strong managerial support for port managers [23] and [22]. However, research dedicated to BAP in bulk ports has received relatively little attention.

Although the BAPs in bulk ports are similar to those in container ports, some unique characteristics differentiate them. A significant difference is that the bulk vessels can only be allocated to the berthing position where the installed handling equipment can serve the cargo type on the vessel. In other words, berth assignments at bulk ports are more restrictive than container ports. [24] establish innovative models and solution algorithms specifically for BAP in bulk ports, which highlights the specific features of bulk port operations, that is, the cargo type of vessels and the equipped handling facilities of berths. Furthermore, the cargo type restricts the berthing position and influences the service starting and completion time. For instance, specific cargo can be discharged from the vessel only when its storage places can accommodate the corresponding quantity. [2] model stock level constraints but not consider the time-variant property of the stock that is changing with the loading or discharging process. Besides, [10] and [19] stress that the unavailability of berths frequently appears in practice because of extreme weather or maintenance requirements. However, few studies have focused on the BAP model for bulk ports with stock level restrictions, let alone combing it with unavailability considerations.

This paper presents a Mixed-Integer Programming (MIP) model for the hybrid BAP in bulk ports, which explicitly considers the constraint of time-variant stock level and practical unavailability. We use the commercial software CPLEX to obtain solutions for a set of instances, and the results show the effectiveness of the proposed model.

2 Related Work

Operational problems related to BAP have been widely investigated within the context of container ports. For more details, we recommend readers to refer to [3] and [4].

The layout of the terminals is generally categorized as discrete, continuous, and hybrid. As shown in Fig. 1, in the continuous BAP, the calling vessels can berth at any position along the quay line. In the discrete BAP, the quay line is separated into different berths, and the calling vessels can only occupy at most one berth. Obviously, the continuous case can better use the quay, but it also increases calculation complexity. While the hybrid BAP allows the continuous case and the discrete case to happen simultaneously; thus, it is more flexible. In Table 1, we list the related work on BAP in bulk ports. We group them according to four feature categories: objective, type, method, and practical

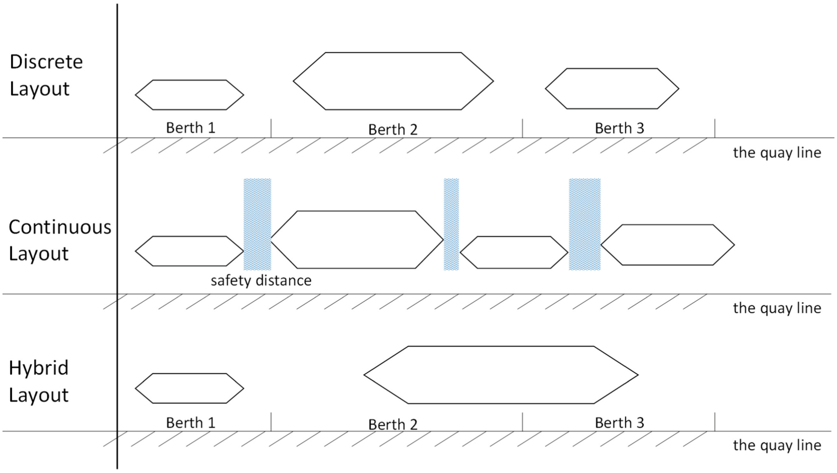

Fig. 1. Three types of the berthing layout.

considerations. Two different main objectives are identified: time-based and cost-based. Type refers to three layouts as illustrated in Fig. 1. The solution method can be divided into heuristics or exact algorithms. The practical considerations include the integrated problem, stock level, night operation permission, specific cargo type, unavailability, and tidal constraints.

Some studies focus on the optimization of individual berth allocation. [25] model and solve the hybrid BAP in bulk ports to minimize the duration time of all vessels. In bulk ports, specialized equipment is required to handle specific types of cargo; for instance, liquid bulk is generally discharged using pipelines installed at only certain sections along the quay. Thus, the BAP model for bulk ports has to incorporate the cargo type on the vessel and the handling equipment fixed on the berths. The authors propose an exact solution based on generalized set partitioning and a heuristic method based on squeaky wheel optimization to obtain near-optimal solutions for the large problem size. Some practical factors that can influence the decision-making process of berth allocation have been considered in the literature. [8] and [6] address the continuous BAP considering the constraints of tides which can influence the departure time of full loaded vessels. Since the stock level of the specific cargo type must be kept in some range for safety consideration, the decision to load or discharge vessels should also consider stock level. [2] propose an integer linear programming model based on discrete BAP, which considers not only tidal effects but also the stock level. A Simulated Annealing-based (SA) algorithm is designed to find reasonable solutions for difficult instances. [9] propose a continuous BAP model with the objective to maximize the daily throughput of the terminal and, at the same time, minimize the delay of ships' departure. In fact, all the studies mentioned above aim to minimize the berthed time of vessels. [19] present a discrete BAP with the objective to minimize the costs (demurrage) incurred. The maintenance of the berth, another practical factor, is also considered in the model, which means that some berths cannot receive vessels at a particular time.

The other operational problems are often interrelated to the decisions of berth allocation; thus, there are some papers studying integrated BAP. [14] and [15] study the integrated problem of berth allocation and handling equipment assignment, but they are focused on container transshipment terminals. [17] address the integrated berth allocation with handling equipment assignment. [18] develop a Decision Support System (DSS) for the port authority to make decisions on berth and ship unloader assignment to minimize the waiting time, operating time, and ships priority deviation. [5] integrate the BAP with yard management by considering constraints of the storage position in berth allocation operation. Real bulk port data is used to validate the model, and the results show that the model can work with up to 40 vessels within reasonable computational time. [20] discuss how to combine the berth and yard assignment to be a single large-scale optimization problem with the objective to minimize the total service time for all vessels berthing at the port. A branch-and-price algorithm is proposed to solve the integrated problems. [12] propose a novel machine learning-based system to coordinate the berthing and yard activities. Based on that, they also insert vessel-specific buffer time to increase the robustness of the results in response to disruption [13]. [26] establish a systematical planning model from berth allocation to yard storage in dry bulk terminals. They also incorporate the tidal time windows in the modal to increase the applicability of the proposed method in real-world terminals. Following the trend of sharing economy, some scholars have seen the potential of collaboration among terminals within one port [16]. [7] consider the continuous BAP and [10] study the discrete BAP for multiple continuous quays in bulk terminals.

3 Model Formulation

This section first describes the berth allocation process in bulk ports and then introduces the relevant notations. Next, it develops a Mixed-Integer Programming (MIP) model and the linearized formulation.

3.1 Problem Description

Figure 2 shows an illustrative example of the process for berth allocation in bulk ports. In this context, we consider a set of vessels $N = \{1, 2, \ldots, |N|\}$ that will call at the port within the planning horizon $T = \{0, 1, \ldots, |T|\}$. We discrete the quay into a set of berths $M = \{1, 2, \ldots, |M|\}$. The berth features (e.g., length, draft, and installed equipment) limit the vessels they can serve. We define M_i to represent the set of berths that vessel i can be served. In practice, the stock level of each cargo type has to be satisfied during loading or discharging operations. For example, the vessel cannot be discharged if the terminal's stock level of the corresponding cargo carried by some vessels would exceed the capacity,

Table 1. An overview related to the literature on the BAP in bulk ports

Reference	Objective		Type			Method		Practical considerations					
	Time	Cost	D	C	H	ES	HS	I	S	N	M	U	T
Perez and Jin [17]	✓		✓			✓		✓					
Ernst et al. [8]	✓			✓		✓							✓
Lassoued and Elloumi [11]	✓		✓			✓							
Barros et al. [2]	✓		✓				✓		✓				✓
Umang et al. [25]	✓				✓	✓	✓				✓		
Robenek et al. [20]	✓		✓			✓		✓					
Pratap et al. [18]	✓	✓	✓				✓	✓					
Hu et al. [9]	✓			✓			✓						
Unsal and Oguz [26]	✓		✓			✓		✓					
Peng et al. [16]	✓	✓	✓			✓	✓	✓					
Cheimanoff et al. [6]	✓			✓			✓						✓
Ribeiro et al. [19]		✓	✓				✓					✓	
Cheimanoff et al. [7]	✓			✓			✓	✓					✓
Krimi et al. [10]		✓		✓			✓	✓				✓	
Andrade and Menezes [1]	✓	✓	✓				✓	✓					
Bouzekri et al. [5]		✓			✓	✓		✓				✓	
de Leon et al. [12]	✓		✓				✓						
de Leon et al. [13]	✓		✓				✓				✓		
This paper		✓			✓	✓			✓	✓	✓	✓	

Type: D (Discrete), C (Continuous), H(Hybrid)
Method: ES (Exact Solution), HS (Heuristic Solution)
Feature: I (Integrated with other problems), S (Stock level), N (Night operation permission), M (Multiple cargo types on one vessel), U (Unavailability), T (Tide)

even though the berth is idle. These vessels can only wait until there is sufficient capacity. Determined by the length of the vessels and berths, we allow one vessel to occupy two berths simultaneously. Some unavailability constraints may arise due to weather conditions or facility breakdown; for instance, cranes must undergo planned maintenance in order to stay in a good performance. To sum up, the hybrid BAP model for bulk ports in this paper incorporates the following points:

(1) One vessel is allowed to occupy two berths under the setting of the hybrid layout.
(2) The unavailability time window of each berth is considered, which can be caused by weather conditions, maintenance requirements, or other stochastic factors.
(3) Each vessel has the earliest and the latest service time. This time window is related to the expected arrival time and the priority of the vessel.
(4) The stock level of each cargo type changes with the loading or discharging process, and the stock level of the corresponding cargo type should be within the range of deadstock and capacity.

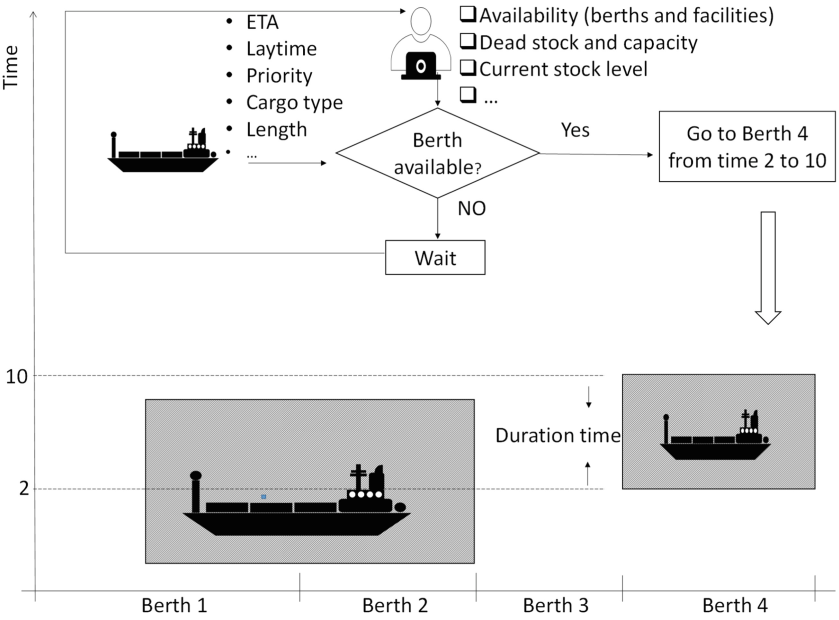

Fig. 2. The berth allocation process in bulk ports

3.2 Notation

Sets

- N: Set of all vessels, $N = \{0, 1, \cdots, |N|\}$;
- M: Set of berths, $M = \{0, 1, \cdots, |M|\}$;
- M_i : Set of berths that can serve vessel i determined by cargo types;
- T: Set of time periods, $T = \{0, 1, \cdots, |T|\}$;
- Θ: Set of product types, $\Theta = \{0, 1, \cdots, |\Theta|\}$;

Parameters

- l_i: the length of vessel i;
- $r_{i\theta}$: rate of operation of vessel i on cargo type θ;
- $q_{i\theta}$: quantity of cargoes on vessel i for cargo type θ;
- t_i: expected arrival time of vessel i;
- h_i: processing time of vessel i;
- g_i: laytime of vessel i;
- c_i: hourly demurrage cost of vessel i;
- $[\alpha_i, \beta_i]$: start time window for vessel i (α_i is related to arrival time of vessel, and β_i is related to priority and roud-trip duration)
- $w_{l\theta}$: dead inventory level of cargo type θ;
- $w_{h\theta}$: capacity of the inventory level of cargo type θ;
- $w_{0\theta}$: current inventory level of cargo type θ at the start of planning horizon;
- b_k: the position of berth k;

- L_k: the maximum length of berth k;
- $[s_k, e_k]$: berth k is available to serve vessels from time s_k to e_k;

Decision Variables

- x_{ik}: equal to 1 if berth k is the start section of vessel i, and 0 otherwise;
- y_{ijk}: equal to 1 if vessel i and vessel j are both assigned to berth k and vessel i is processed before vessel j, and 0 otherwise;
- st_i: the starting time of vessel i;
- z_{ik}: equal to 1 if vessel i is berthed at k and $k+1$, and 0 otherwise, $k \in [0, 1, \ldots, |M|-1]$;
- γ_{it}: equal to 1 if vessel i is berthed at time t, and 0 otherwise;
- ξ_{it}^{θ}: equal to 1 if cargo type θ of vessel i are operated at time t, and 0 otherwise;

3.3 Model

With the notation defined above, we propose the formulation of the hybrid BAP in bulk ports with unavailability and stock constraints, which specifically considers the situation of multiple cargo types on one vessel.

$$min \quad z = \sum_{i \in N} c_i (ct_i - t_i - g_i)^+ \tag{1}$$

Subject to:

$$\sum_{k \in M_i} x_{ik} = 1 + \sum_{k \in M \setminus \{|M|\}} z_{ik} \quad \forall i \in N \tag{2}$$

$$st_i \geq t_i \quad \forall i \in N \tag{3}$$

$$st_i \leq \gamma_{it} * t + M(1 - \gamma_{it}) \quad \forall i \in N, t \in T \tag{4}$$

$$st_i + h_i \geq \gamma_{it} * (t+1) \quad \forall i \in N, t \in T \tag{5}$$

$$\sum_{t \in T} \gamma_{it} \geq h_i \quad \forall i \in N \tag{6}$$

$$ct_i \geq st_i + h_i \quad \forall i \in N \tag{7}$$

$$\sum_{i \in N} st_j \geq ct_i - M(1 - y_{ijk}) \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{8}$$

$$y_{ijk} + y_{jik} \leq 0.5(x_{ik} + x_{jk}) \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{9}$$

$$y_{ijk} + y_{jik} \geq x_{ik} + x_{jk} - 1 \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{10}$$

$$x_{ik} + x_{i,k+1} \geq 2z_{ik} \quad \forall i \in N, k \in M \setminus \{|M|\} \tag{11}$$

$$\sum_{k \in M \setminus \{|M|\}} z_{ik} \leq 1 \quad \forall i \in N \tag{12}$$

$$l_i x_{ik} \leq \sum_{k \in M} L_k x_{ik} \quad \forall i \in N, k \in M \tag{13}$$

$$\sum_{\theta \in \Theta} \xi_{it}^{\theta} = \gamma_{it} \quad \forall i \in N, t \in T \tag{14}$$

$$\gamma_{i\theta} * \sum_{t \in T} \xi_{it}^{\theta} \geq q_{i\theta} \quad \forall i \in N, \theta \in \Theta \tag{15}$$

$$w_{l\theta} \leq w_{0\theta} + \sum_{i \in N} \sum_{m=0}^{m=t} \gamma_{i\theta} * \xi_{it}^{\theta} \leq w_{h\theta} \quad \forall t \in T, \theta \in \Theta \tag{16}$$

$$x_{ik} * s_k \leq st_i \leq x_{ik} * (e_k - h_i) \quad \forall i \in N, k \in M \tag{17}$$

$$\alpha_i \leq st_i \leq \beta_i \quad \forall i \in N \tag{18}$$

$$x_{ik} \in \{0, 1\} \quad \forall i \in N, k \in M \tag{19}$$

$$y_{ijk} \in \{0, 1\} \quad \forall i \in N, j \in N, i \neq j, k \in M \tag{20}$$

$$\xi_{it}^{\theta} \in \{0, 1\} \quad \forall i \in N, t \in T, \theta \in \Theta \tag{21}$$

$$z_{ik} \in \{0, 1\} \quad \forall i \in N, k \in M \backslash \{|M|\} \tag{22}$$

$$\gamma_{it} \in \{0, 1\} \quad \forall i \in N, t \in T \tag{23}$$

The objective function (1) is to minimize the demurrage fee of all vessels. Constraint (2) ensures each vessel i occupies at least one berth. Constraint (3)–(7) restrict the completion time and the start time of Vessel i. Constraints (8)–(10) are no overlapping restriction for vessels that be served at the same berth. Constraints (11)–(13) allow vessels to occupy two berths. Constraints (14)–(16) ensure that the current inventory during the loading or discharging of vessels can satisfy the requirement of stock of specific cargo type. Some practical factors which restrict the starting time and completion time of vessels are considered in this model. Constraint (17) represents the available time window of berths. Constraint (18) is the available time window of vessels. Constraints (19)–(23) specify the range of decision variables. The objective function (1) is nonlinear. Thus, they need to be linearized by defining an additional decision variable $\mu_i = (ct_i - t_i - g_i)^+$. The related additional constraints are defined as follows:

$$\mu_i \geq 0 \quad \forall i \in N \tag{24}$$

$$\mu_i \geq ct_i - ti - g_i \quad \forall i \in N \tag{25}$$

Therefore, the model can be reformulated as a mixed-integer linear program as follows:

$$min \quad z = \sum_{i \in N} c_i \mu_i \tag{26}$$

Subject to Constraints (2)–(25).

4 Numerical Experiments

In this section, the MIP model proposed in Sect. 3.3 is tested using the CPLEX solver with the computational limit of 600 s. All tests are running on an Intel

Core i5 (1.7 GHz) processor and use the version of CPLEX 12.8.0 under the C++ environment. We introduce the instance generation first and then analyze the model's performance under four different scenarios.

4.1 Generation of Instances

We generate 12 instance sizes with different $|M|$ and $|N|$ as well as the consideration of unavailability and multiple cargo types within the time horizon of one week, as shown in Table 2. The unavailability can be incurred by maintenance requirements for facilities, extreme weather, or other unforeseen factors. The length of vessels and berths are generated following a uniform distribution of $[80, 180]$ and $[120, 160]$. The other detailed attributes related to the vessel are generated randomly, including arrival time, processing time, laytime, demurrage, night operation permission, and the cargo tonnage and type they carried.

Table 2. Information about the generated instances

Instance	$\|N\|$	$\|M\|$	Unavailability	Multiple cargo types
I1	6	3	No	Single
I2	6	3	Yes	Single
I3	12	3	No	Single
I4	12	3	Yes	Single
I5	18	3	No	Single
I6	18	3	Yes	Single
I7	6	5	No	Multiple
I8	6	5	Yes	Multiple
I9	12	5	No	Multiple
I10	12	5	Yes	Multiple
I11	18	5	No	Multiple
I12	18	5	Yes	Multiple

4.2 Results Analysis and Discussion

As highlighted in Sect. 2, the night berthing permission is considered in our model; thus, for those vessels that cannot be operated during the night (assumed from 1 am to 6 am), the following constraints (27) and (28) are added:

$$\begin{aligned} & st_i - \gamma_{iq} * t - M(1 - \gamma_{iq}) < 0 \\ & \forall i \in N, q \in [p * 24 + 1, p * 24 + 5], p \in [0, 31], t = p * 24 + 1 \end{aligned} \tag{27}$$

$$\begin{aligned} & ct_i \geq \gamma_{iq} * t \\ & \forall i \in N, q \in [p * 24 + 1, p * 24 + 5], p \in [0, 31], t = p * 24 + 5 \end{aligned} \tag{28}$$

Table 3 shows the result of the expected demurrage fee and the computational time. The proposed MIP model can find the optimal solutions for all 12 instances by applying CPLEX, with up to 18 vessels and 5 berths. In Fig. 3, we compare the demurrage fee in four scenarios which differentiate in whether consider multiple cargo types and unavailability or not. We find that berths' unavailability can always significantly increase the demurrage fee, especially when the berths are busy. However, the multiple cargo types on the same vessel have no significant impact when the port is idle, but it will obviously increase demurrage fees when the port is busy.

Table 3. Computational results for the proposed MIP model

Instance	Obj ($)	Time (s)	Instance	Obj ($)	Time (s)
I1	4347.00	1.64	I7	4036.50	2.28
I2	7762.50	1.27	I8	4657.50	0.80
I3	4968.00	11.36	I9	3283.15	2.50
I4	5267.00	19.17	I10	4621.50	4.89
I5	7464.00	179.38	I11	6110.00	24.34
I6	8393.50	240.02	I12	29330.00	306.67

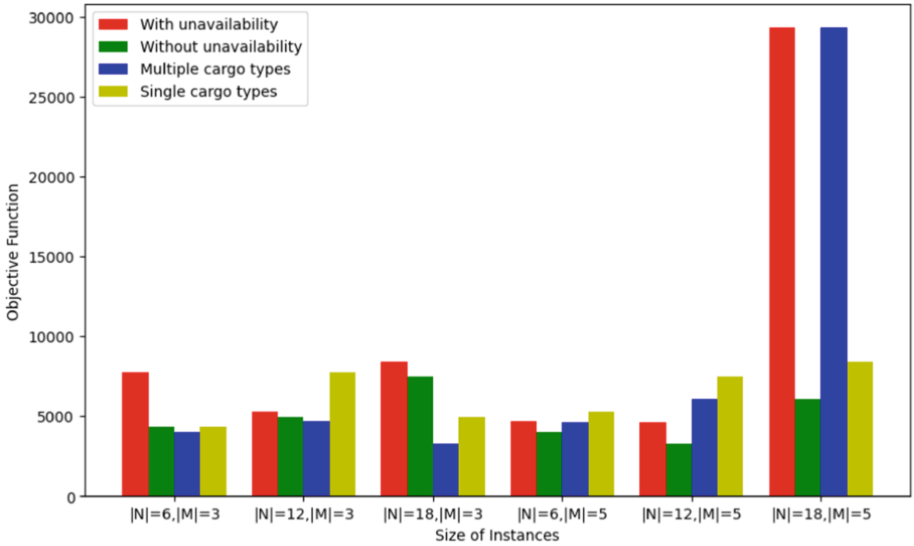

Fig. 3. The comparison of demurrage fee under four different scenarios

4.3 Managerial Insights and Policy Implications

This paper proposes a hybrid BAP model for bulk port managers to decide when and where to operate on the calling vessels considering the constraints of the unavailability of facilities and the stock level. With the experimental results in Sect. 4.2, the following implications are provided for the bulk port managers:

(1) In practice, unavailability of berths happens frequently, caused by many practical factors, such as extreme weather and facility maintenance. The BAP model, which ignores the unavailability, does not work in many practical applications and even makes the port into trouble. In addition, the unavailability of berths can significantly influence the berth allocation plan and further impact the total demurrage fee. Thus, the bulk port managers should consider the unavailability when making decisions on berthing plans.
(2) Constraints (27) and (28) are for satisfying the requirement of individual vessels on night berthing permissions and thus improve the customer service level of the ports.
(3) Whether to consider stock level constraints largely depends on the actual situation of the ports. When the storage is approaching capacity, it is necessary to consider the stock level limitation in berth allocation. Otherwise, the vessel must wait until there is enough storage space, which can also make the ports into trouble.

5 Conclusions

Prior work on mathematical models and algorithms has solved the basic BAP in bulk ports. In [24], for instance, the author reports the specific features of berth operations in bulk ports that distinguish them from container ports. However, these studies have either ignored some practical constraints (e.g., unavailability of berths and storage) or have not considered the multiple cargo types on one vessel, which can make it hard to apply those approaches under real-world conditions. In this work, we propose a hybrid BAP model for bulk ports with unavailability and stock level constraints, and we consider the case of multiple cargo types on one vessel specifically. We show the effectiveness of the proposed model by conducting numerical experiments on a set of distinct instances. The hybrid BAP extends earlier work of [25], providing a better fit for the loading or discharging operations in real-world bulk ports. The commercial software CPLEX can obtain optimal solutions with up to 18 vessels within 600 s. Most notably, this is the first study to our knowledge that dedicates itself to the BAP in bulk ports and considers unavailability and stock constraints simultaneously. Our solutions provide timely and effective decision support to port managers. However, our model can not solve large-scale instances by CPLEX within a reasonable computing time. Future work should therefore develop some algorithms for larger instances.

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