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Comparative analysis of berth allocation problem solving under different berth function assigning

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ABSTRACT

This paper focuses on the efficiency analysis of berth allocation problem under the different berth function assigning. The consideration of berth function assigning is divided in two cases: multi-purpose berth and single-purpose berth. The discrete and dynamic problem of berth allocation problem with multi-purpose berth and single-purpose berth are investigated. To solve the resulting problem, a mixed-integer programming model is proposed to find the optimal solutions for both scenarios. Furthermore, numerical experiments are carried on randomly generated instances to assess the effectiveness of the proposed model and comparative analysis in the different berth function. Computational examples show that the performance of berth allocation problem with multi-purpose berth outperforms the single-purpose berth in term of total service time of vessel and confirm that the multi-purpose berth is increased flexibility in port operation management in case of fluctuate demand.

1. Introduction.

Nowadays, economic, technological, and social aspects are constantly evolving. These changes reinforce a more competitive environment, especially in maritime trade. For example, international trade volumes are increasing, resulting in an increase in the size of cargo ships and increased investment in berth infrastructure. Larger vessels, higher volatility and increased competition require ports to improve efficiency to meet new challenges and constraints. When considering the current demand for cargo handling between countries, berths are still handling higher cargo demand, which could lead to an overcapacity situation, which is common in many berths around the world. This has become a problem. Such problems are caused by past berth investments and inefficient advice when a berth is no longer in use.

Therefore, after capacity assessment, berth operators need to make effective investment decisions for the development of new berths while improving existing berths to deal with such situations effectively and efficiently.

Key strategies for berth improvement focus on changes to berth services to meet increased demand. Especially the expansion of the terminal to accommodate larger goods and support the demand for diverse products with increased volatility in each period. Due to the above strategies, many berths require complex operations, including flexibility, and require powerful tools to achieve maximum efficiency in berth management.

The Berth Allocation Problem (BAP) is one problem in seaside operations and has been affected by the expansion and the adjustment of the berth's service model according to current competitive strategy. There were also issues with berth management for each ship, such as prioritizing berth use, allocating berth areas according to the layout, and allocating berth usage time for ships entering the port. For spatial allocation, there are three types of wharf layouts, discrete layout, con-

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tinuous layout, and hybrid layout (Bierwirth & Meisel, 2010). BAP problems can be classified according to the ship's arrival time, which are static arrival and dynamic arrival (Imai et al., 2001). The BAP problem has attracted the attention of past and present researchers and many solutions have been developed. The static variant of discrete BAP was first formulated by Imai et al., (1997) and the dynamic variant was discussed by Imai et al., (2001). References (Bierwirth & Meisel, 2010 , Bierwirth & Meisel, 2015, and Carlo et al., 2015) are recent reviews of the literature on coastal operations involving BAPs. Many methods with both exact and approximate properties have been proposed to solve BAP. For example, the study in Jos et al. (2019) developed a new mixed-integer linear programming (MILP) model to deal with the BAP to reduce operating costs. Some authors Lassoued, & Abdelkarim (2019) proposed a mixed integer programming (MIP) model to minimize the total service time of a ship considering the ship arrival time in a discrete space. Another work Kavoosi et al. (2019) also presents a solution to his BAP through the use of evolutionary algorithms (EA), particle swarm optimization (PSO), and differential evolution (DE). A genetic algorithm (GA) was developed in Hsu et al. (2019) to solve BAP. Additionally, authors in Prencipe, & Marinelli (2021) proposed a new mathematical formulation in the form of the MILP model to solve Discrete and Dynamic Berth Allocation Problem (DDBAP). Moreover, a new solution is adopted to optimize Bee Colony Optimization (BCO) based metaheuristic approach to solve large-scale BAP.

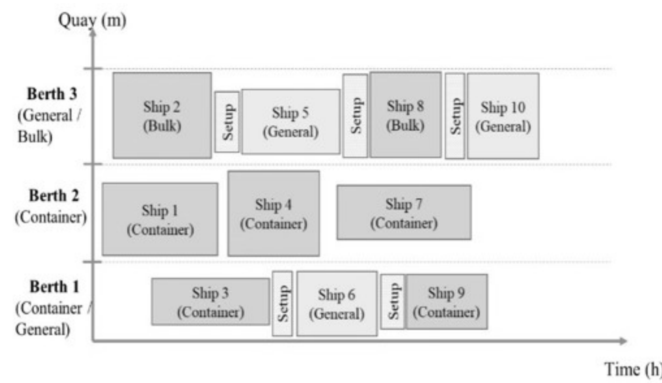
Previous studies have found that the characteristics of the BAP problem view determine the specific berth positions of individual berths. However, expanding the berth area and service offering creates multiple berths dedicated to servicing different types of cargo ships at each berth. Recently, the development of berths and equipment to support more than one type of cargo in the same berth or multi-purpose berth to increase the flexibility of terminal management in case of need while taking more or fewer products for each product category, as can be seen in Fig. 1. There were few research studies on BAP with multi-purpose berth in the past. For example, in Grubisic et al. (2014) a mixed integer programming (MIP) model was proposed to study the impact of solving the berth assignment problem (BAP) according to different river port design options. Multi-purpose and dedicated berth layouts are compared with port efficiency requirements, allowing the best design option to be selected based on berth allocation. In another study Xie et al. (2021), a multi-purpose port with wharf space restriction in Indonesia was examined and the importance and contribution of simulation models in product evaluation and the capacity of the port were revealed. Moreover, the author in Sangsawang, & Longploypad (2022) studies the problem of Multi-Quay Berth Allocation Problem (MQ-BAP) includes multi-purpose berth. A mixed-integer programming and metaheuristic solution approach based on Genetic algorithm (GA) are proposed to find an effective method for berths allocation.

Thus, this research aims to study BAP problem with multi-purpose berth, which is flexible berth management to enhance effective berth management and compare problems of BAP with single-purpose berth which is the traditional berth management procedures. The setup time of berths that are multi-purpose berths are also considered. When the preceding and subsequent service vessels have different types of cargo to be handled or sequence dependent setup time. The remainder of this article is organized as follows. Section 2 presents the problem description and formulation. While the result and analysis are discussed in section 3. Finally, section 4 described the conclusion.

2. Problem description and formulation.

This section explains the detail of BAP with multi-purpose berth and BAP with single-purpose berth. Besides that, the assumption and formulation of mixed-integer programming (MIP) of both models are described.

Figure 1: An illustration of multi-purpose berth (berth 1 and 3) and single-purpose berth (berth 2).



Source: Authors.

2.1. Problem Definition.

This study addresses BAP with multi-purpose berth and BAP with single-purpose berth, where discrete berthing layout is considered. The quay is divided into a number of berth $i \in I$ and berth can service one vessel at a time. In each berth, there is an eligibility constraint C_{ij}, which mean the compatibility between berths and ships (i.e., cargo type, length of berth, depth of berth). Moreover, setup times of berth X_{hj} may arise due to the changing of berth type according to the sequence of assigning ships. There is a set of arriving ships $j = 1, 2, 3, \ldots, J$ along with the attribute of cargo type and each ship $j \in J$ has multiple known characteristics, including Expected Time of Arrival (A) and Handling Time (H). The objective of this study is to determine the berthing position and berthing time for all arriving ships in J to minimizing total service time of all ships. The total service time is defined as the total duration of time between arrival of the vessel to its departure from the port.

2.2. MIP model for BAP with single-purpose berth.

2.2.1. Assumptions.

1. Assume that a set of vessels are set to arrive at a port over a period and serviced at a number of berths.
2. All berths are assumed to be free at the initial state.
3. Each ship corresponds at least to one compatible berth due to the discrete layout of quays.
4. A berth is considered as a specific point on the quay (referred to by number).
5. Each berth can be dedicated for only one type of cargo and vessel.
6. Compatibility between ships and berths is related to geometric and cargo type constraints.
7. One ship can occupy only one berth and not allowed to interrupt the operations when a vessel start operations at a particular berth.

2.2.2. Mathematical Formulation.

The notation used in the MIP model for BAP with single-purpose berth is presented in Table 1.

Table 1: Indexes used in the MIP Model.

Notation	Description
I	Set of berths, indexed by $i = 1,2,3,\dots,I$
J	Set of ships, indexed by $j, h = 1,2,3,\dots,J$
K	Set of service orders, indexed by
P_k	Subset of K such that $P_k = \{p \mid p < k \in K\}$
W_i	Subset of ships with $A_j \geq B_i$
C_{ij}	$\begin{cases} 1 & \text{if berth } i \text{ is capable of berthing ship } j \\ 0 & \text{Otherwise} \end{cases}$
A_j	Arrival time of ship j
H_j	Handling time of ship j
B_i	Initial available time of berth i
M	Very large positive number
Y_{ijk}	$\begin{cases} 1 & \text{if ship } j \text{ is berthing as the } k^{th} \text{ ship at berth } i \\ 0 & \text{Otherwise} \end{cases}$
D_{ijk}	Idle time of berth i between the departure of the $(k-1)^{th}$ ship and the arrival of the k^{th} ship when ship j is berthing as the k^{th} ship
O_{ik}	Arrival time of the k^{th} ship at berth i
R_{ik}	Start time of handling the k^{th} ship at berth i
F_{ik}	CT_{ik}Completion time of the k^{th} ship at berth i

Source: Authors.

To finding the global optimal solution of the BAP with single-purpose berth, we modelled the problem as a MIP whose mathematical formulation is given as follows:

Objective function

$$Minimize \sum_{i\in I}\sum_{k\in K}(F_{ik} - O_{ik})\forall i \in I,\ k \in K \tag{1}$$

Subject to

$$\sum_{i\epsilon I}\sum_{k\epsilon K} Y_{ijk} = 1 \forall j \in J \tag{2}$$

$$\sum_{j\epsilon J} Y_{ijk} \leq 1\ \forall i \in I,\ k \in K \tag{3}$$

$$\sum_{j\epsilon J} Y_{ijk+1} \leq \sum_{j\epsilon J} Y_{ijk} \forall i \in I,\ k \in 1\dots K-1 \tag{4}$$

$$O_{ik} = \sum_{j\epsilon J} Y_{ijk} * A_j \forall i \in I,\ k \in K \tag{5}$$

$$R_{ik} \geq \sum_{j\epsilon J} Y_{ijk} * B_i \forall i \in I,\ k \in K \tag{6}$$

$$R_{ik} \geq \sum_{j\epsilon J} Y_{ijk} * A_i \forall i \in I,\ k \in K \tag{7}$$

$$R_{ik+1} \leq M * \sum_{j\epsilon J} Y_{ijk+1} \forall i \in I,\ k \in 1\dots K-1 \tag{8}$$

$$F_{ik} = R_{ik} + \sum_{j\epsilon J} Y_{ijk} * H_{ij} \forall i \in I,\ k \in K \tag{9}$$

$$F_{ik-1} - R_{ik} \leq M * (2 - Y_{ijk} - Y_{ihk-1})$$
$$\forall i \in I,\ \forall\ h, j \in J,\ k \in 2\dots K \tag{10}$$

$$\sum_{l\in J}\sum_{m\in P_k}(H_{il}Y_{ilm} + D_{ilm}) + D_{ijk} - \left(A_j - B_i\right) *$$
$$Y_{ijk} \geq 0 \forall i \in I,\ \forall\ j \in W_i,\ k \in K \tag{11}$$

$$Y_{ijk} \leq C_{ij} \forall i \in I,\ \forall j \in J,\ k \in K \tag{12}$$

$$Y_{ijk}\ \{0,1\} \forall i \in I,\ \forall j \in J,\ k \in K \tag{13}$$

$$D_{ilm}\ \ 0,\ int \forall i \in I,\ \forall j \in J,\ k \in K \tag{14}$$

$$O_{ik},\ F_{ik}, R_{ik}\ \ 0,\ int \forall i \in I,\ k \in K \tag{15}$$

The objective function (1) is to minimize the total service time of all ships. Constraints (2) ensure that every ship must be serviced at some berth in any order of service. Constraints (3) enforces that every berth services up to one ship at any time. Constraints (4) ensure the service order k and $k+1$for the same berth. Constraints (5) set an arrival time of the k^{th} ship at berth i equal to Arrival time of ship j. Constraints (6) define a time to start handling the ship of every berth is greater than or equal to time when berth become available. Constraints (7) define a time to start handling the ship of every berth is greater than or equal to arrival time of ship. Constraints (8) from 2nd order onwards, if none of ship berthing as the k^{th} ship at berth i, then start time of handling the k^{th} ship at berth i equal to 0. Constraints (9) define the completion time of handling the k^{th} ship at berth i. Constraints (10) ensure that if both ships h and j are serviced by the same berth and ship h is serviced before, the completion time of handling ship h should come before the start time of handling ship j. Constraints (11) assure that ships must be serviced after their arrival. Constraints (12) A set of berth eligibility restrictions. Constraints (13) define the binary nature of the decision variable. Finally, constraints (14) and (15) define the decision variable as greater than or equal to 0.

2.3. MIP model for BAP with multi-purpose berth.

In this case, each berth can be dedicated for one or two different types of cargo and vessels. Under this assumption, MIP model for BAP with single purpose berth can be modified for multi-purpose berth. All notations and constraints of the original model are still valid except constraints (10). The additional decision variables and modifications to the model are presented below.

Notations

X_{hj} Setup time to berthing ship j after ship h on the same berth.

Subject to

$$F_{ik-1} + X_{hj} - R_{ik} \leq M * (2 - Y_{ijk} - Y_{ihk-1})$$

$$\forall i \in I,\ \forall\ h, j \in J,\ k \in 2 \ldots K \quad (16)$$

Constrains (16) define the completion time of handling the k^{th} ship at berth i that consist of handling time ship and setup time of berth. New constraints (16) is modified to replace constraints (10).

3. Computational experiments.

In this section, we conducted computational experiments using randomly generated test problems to find the global optimal solution of both BAP. ILOG CPLEX 12.10 is used to obtain the optimal solution through MIP as presented in Section 2. All experiments are executed on a PC Intel® Core^{TM} i5 2.30 GHz with 8 GB of RAM.

This experiment is divided into 2 cases, first is the comparisons between BAP with single-purpose berth and BAP with partial multi-purpose berth, and second is the comparisons between BAP with single-purpose berth and BAP with fully multi-purpose berth. Partial multi-purpose berth means the number of berths that are multi-purpose not more than 50% of all berths. While fully multi-purpose berth means that all berths are multi-purpose.

For both comparison cases, we generate 18 test instances for each case. All cases comprise number of berths, number of ships, number of cargo types, ship handling times, setup time of berth, inter-arrival time of ships, and planning horizon as shown in table 2. Moreover, according to the problem constraint, at least one berth must be compatible with each ship in terms of length, draft, and cargo type.

Table 2: Test problem data.

Data	Details
number of berths	3,4, and 5 berths
number of ships	7,10, and 13 ships
number of cargo types	3 types
ship handling times	6 to 48 hours
Setup time of berth	1 to 3 hours
Inter-arrival time of ships	0 to 3 hours
planning horizon	12 to 48 hours

Source: Authors.

3.1. The comparisons between BAP with single-purpose berth and BAP with partial multi-purpose berth.

The results of the comparison between BAP with single-purpose berth and BAP with partial multi-purpose berth are reported in Table 3.

Table 3: Result comparison of case 1.

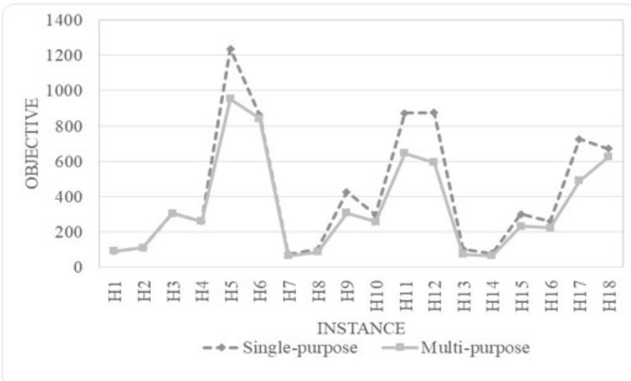
Instance	Problem size (BxS)	Planning Horizon (Hrs.)	Handling Time (Hrs.)	CPLEX Results (Hrs.)		
				Single	Multi$_p$	Gap (%)
H1	3x7	12	6,12	91	91	0%
H2	3x7	12	6,12	109	109	0%
H3	3x10	24	12,24	304	304	0%
H4	3x10	24	12,24	260	260	0%
H5	3x13	48	12,48	1238	954	-23%
H6	3x13	48	12,48	863	842	-2%
H7	4x7	12	6,12	73	64	-12%
H8	4x7	12	6,12	101	86	-15%
H9	4x10	24	12,24	426	307	-28%
H10	4x10	24	12,24	295	256	-13%
H11	4x13	48	12,48	873	646	-26%
H12	4x13	48	12,48	874	593	-32%
H13	5x7	12	6,12	101	73	-28%
H14	5x7	12	6,12	77	65	-16%
H15	5x10	24	12,24	301	231	-23%
H16	5x10	24	12,24	259	223	-14%
H17	5x13	48	12,48	726	490	-33%
H18	5x13	48	12,48	672	623	-7%

Notes. B denotes the number of berths. S denotes the number of ships. Single denotes BAP with single-purpose berths. Multi$_p$ denotes the BAP with partial multi-purpose berths.

Source: Authors.

We found that the best solution from CPLEX in case of BAP with partial multi-purpose shows the objective function gap, compare with CPLEX in case of BAP with single purpose, give value by average 15%. This can be seen analyzing the graph of Fig. 2. that shows that BAP with partial multi-purpose berth model reached better result in all instances. From this fig-

Figure 2: Comparisons of ship's total service time (BAP with single-purpose berth and BAP with partial multi-purpose berth).



Source: Authors.

ure, we can conclude that the multi-purpose berth affects to increased flexibility in port operation management which can be seen from the total service time of all ship are shorter although only partially defined.

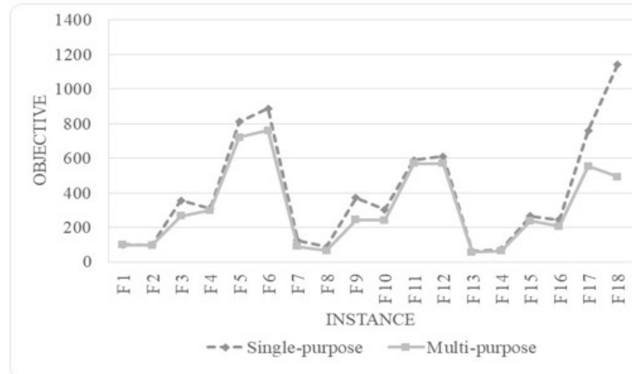
3.2. The comparisons between BAP with single-purpose berth and BAP with fully multi-purpose berth.

Table 4: Result comparison of case 2.

Instance	Problem size (BxS)	Planning Horizon (Hrs.)	Handling Time (Hrs.)	CPLEX Results (Hrs.)		
				Single	$Multi_f$	Gap (%)
F1	3x7	12	6,12	99	98	-1%
F2	3x7	12	6,12	97	95	-2%
F3	3x10	24	12,24	356	266	-25%
F4	3x10	24	12,24	308	297	-4%
F5	3x13	48	12,48	810	720*	-11%
F6	3x13	48	12,48	887	760*	-14%
F7	4x7	12	6,12	125	88	-30%
F8	4x7	12	6,12	86	66	-23%
F9	4x10	24	12,24	371	243	-35%
F10	4x10	24	12,24	303	241	-20%
F11	4x13	48	12,48	588	568*	-3%
F12	4x13	48	12,48	611	568*	-7%
F13	5x7	12	6,12	63	57	-10%
F14	5x7	12	6,12	71	63	-11%
F15	5x10	24	12,24	266	237	-11%
F16	5x10	24	12,24	244	206	-16%
F17	5x13	48	12,48	759	553*	-27%
F18	5x13	48	12,48	1143	491*	-57%

Notes. *B* denotes the number of berths. *S* denotes the number of ships. Single denotes BAP with single-purpose berths. $Multi_f$ denotes the BAP with fully multi-purpose berths. * Best found before the time limitation at 12 hours.
Source: Authors.

Figure 3: Comparisons of ship's total service time (BAP with single-purpose berth and BAP with fully multi-purpose berth).



Source: Authors.

The result of the comparison between BAP with single-purpose berth and BAP with fully multi-purpose berth are reported in Table 4. We found that the best solution from CPLEX in case of BAP with fully multi-purpose shows the objective function gap, compare with CPLEX in case of BAP with single purpose, give value by average 17%. This can be seen analyzing the graph of Fig. 3. that shows that BAP with fully multi-purpose berth model reached better result in all instances. Once again, we can conclude that the fully multi-purpose berth exhibits higher performance in terms of increasing flexibility in port operation management which can be seen from the total service time of all ship are very shorter.

Conclusions.

In this paper, we focused on the efficiency analysis of the discrete and dynamic problem of berth allocation problem with multi-purpose and single-purpose berth. We develop a mixed-integer programming to address the problem, which focuses on the minimizing of the total service time of all ships. Numerical experiments are carried on randomly generated instances to assess the effectiveness of the proposed model and comparative analysis in the different berth function. For a comparison purpose, we set a Numerical experiment in 2 cases: 1) the comparisons between BAP with single-purpose and BAP with partial multi-purpose berth, and 2) the comparisons between BAP with single-purpose and BAP with fully multi-purpose berth. The results show that the performance of BAP with multi-purpose berth has higher efficiency over the single-purpose berth in term of total service time of vessel in both 2 case, partial and fully multi-purpose berth, of experimental by 15% and 17% respectively. Hence, we can conclude that the multi-purpose berth affects to increased flexibility in Berth allocation management especially in terminal that consist of many berths. This study demonstrates effective functional characterization of the new flexible berth model and can be used as a guideline for berth planning effectively.

In the future, we plan to extend the modeling to consider more realistic constraint such as tidal or position dependent handling time. Also, a metaheuristic can be developed to solve large instances. Finally, we plan to improve the performance of metaheuristic in solving the BAP with multi-purpose berth by hybridization or adding a self-adaptation concept.

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