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AN INTEGRATED BERTH ALLOCATION AND YARD ASSIGNMENT PROBLEM FOR BULK PORTS: FORMULATION AND CASE STUDY

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Abstract. The impact of globalization on maritime transportation has led to its enormous growth over the last decade. Due to the rapid increase in sea-borne demand, large emphasis is placed on making ports more efficient, by promoting the effective utilization of available resources. Therefore, the role of optimization becomes crucial, as port operators aim for the cost-effective option of maximizing port efficiency, rather than the costly alternative of expanding existing capacity. One of the most important seaside planning problems that has received a great deal of attention in research streams is the assignment of quay space to incoming vessels; it is known as the Berth Allocation Problem (BAP). Even though it has been studied extensively, there remain certain unaddressed gaps. Relatively little attention has been focused on the operation of bulk ports, in which terminal operators are concerned with integrating and managing the sea-side area (wharf) and the buffer area for storage. The cargo type must be explicitly known to the bulk port operator, who in turn assigns to it the best storage area and the use of appropriate specialized equipment for loading and discharging. It is evident that the integration of the BAP with yard assignment is necessary, in order to maximize efficiency and obtain the optimal berthing plan in bulk ports. Thus, the current paper studies the integrated dynamic hybrid berth allocation and yard assignment problem (BYAP) in the context of bulk ports. Important assumptions are taken into consideration in order to produce a realistic and practical model. Finally, a relevant case study is presented for the case of Mina Zayed Port in Abu Dhabi.

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1. Introduction

Over the past decade, the maritime industry has experienced immense growth, greatly impacting the global economy [1]. The increasing importance of the industry's role in the economy has led researchers to the thorough study of its operations [10]. As demand continues to increase, in order to avoid bottlenecks and increase operational efficiency, research has been recently focusing on the improvement of these operations [8]. Port operators are faced with the decision of expanding resources or maximizing the utilization of existing ones. Obviously, the latter is a more cost-effective option and it is enabled with the help of optimization [27]. Optimization techniques

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are thus increasingly implemented in port operations, which can be distinguished into two main areas, namely seaside and yardside operations [9].

As far as seaside operations are concerned, the three major problems pertaining to this area are the Berth Allocation Problem (BAP), the Quay Crane Assignment Problem (QCAP) and the Quay Crane Scheduling Problem (QCSP) [8, 33]. The BAP aims to assign available berthing spaces to incoming vessels, while the QCAP and the QCSP focus on allocating cranes to vessels, and scheduling the operation of these cranes for the unloading and loading of containers, respectively [17, 30]. The QCSP is inherently complex and as such has received considerable attention from researchers, with recent work incorporating more realistic considerations, such as vessel stability [1, 2, 4] and stochasticity [3, 12].

On the other hand, the BAP has not been studied as thoroughly, especially for the case of bulk ports. In the current work, we relax a number of simplifying assumptions, by incorporating realistic considerations, such as the vessel's length, the draft of the vessel, expected arrival time and handling time. Regarding the spatial constraints, the total length of the quay must be sufficiently large to accommodate the assigned vessels. This is something that has traditionally been ignored, but it is expected to yield more practical results once considered. In the case of bulk ports, a further constraint is enforced, which encourages the berthing of vessels close to the respective yard storage area of the type of cargo they are carrying. It is evident now that the BAP can benefit from integration with the problem of yard management.

Yard management is one of the major challenges in port operations; it involves three main tasks, including the reservation of yard capacity, the selection of storage locations and the repositioning of cargo within the yard [22]. The first task is concerned with utilizing a large space of the yard over time, for more efficient operations. In the case of bulk terminals, a larger storage space is required compared to container terminals and the type of cargo must be taken into consideration. One advantage of bulk terminals is that there is no risk of disorganizing or reshuffling of cargo. On the other hand, storage location requires special attention, as it may cause bottlenecks. In container terminals, an import container cannot be reserved at the same area as an export container. The specific yard blocks dedicated to export containers mainly aim to minimize container reshuffling in the storage yard, during the vessel service time. This was shown to be the stacking policy provided by [6], where containers of the same class are stored in the same yard stack, providing flexibility for container exchange within similar classes. For example, an export container to be soon loaded onto a vessel will be placed at the top of the stack; on the other hand, import containers are not exchangeable and so minimizing the number of reshuffles poses no advantage. It is a different case in bulk ports; selection of the storage area may not pose a challenge, as the yard location assigned to a certain type of cargo is in most cases determined from the beginning. Additionally, the purpose (export or import) does not play a role, as all cargo material is accumulated. Overall, simpler assumptions hold for bulk ports, which is why they have not received as much attention as container terminals. However, there remain issues and gaps to be addressed in the yard management of bulk ports, and this is one of the objectives of the current work.

In summary, the current work aims to address the integrated problem of berth allocation and yard management in bulk ports. Despite the extensive research conducted for container terminals, little emphasis has been given to bulk ports, which is why it is of interest to address this special case, in which additional circumstances are taken into consideration during the modeling process. These include the assignment of a berthing position to a ship such that it can optimally accommodate its cargo to the yard storage. Furthermore, we relax a number of simplifying assumptions of the BAP in bulk ports, such as the assumption of unified storage areas, in order to allow the model to yield more practical solutions. The contribution of the work is highlighted through an extended formulation, based on the work of [25]. Furthermore, a case study is presented on the port of Mina Zayed in Abu Dhabi.

The remainder of this paper is structured as follows: Section 2 is dedicated to providing an overview of the relevant literature, with a focus on the BAP. Section 3 introduces the problem through a detailed description, followed by the problem formulation. In Section 4, the case study of the port in Abu Dhabi is presented, before concluding the work in Section 5.

2. Literature review

The purpose of this section is to provide a thorough and comprehensive overview of existing works that address the Berth Allocation Problem (BAP) and the Yard Assignment Problem (YAP). Several notable works are presented that formulate these problems independently, as well as using an integrated approach, adopted more recently. The prevalent assumptions and techniques are addressed, while the various gaps that the current work aims to address are identified. Finally, the section is concluded with the characteristics of the present work.

Several distinctions can be found with respect to the considerations of the problem addressed. A first distinction has to do with the arrival times of vessels. If vessels are already berthed at the port, this is called the Static Berth Allocation Problem (SBAP), while if the arrival times occur during the planning horizon it is known as the Dynamic Berth Allocation Problem (DBAP) [29] study the SBAP and develop a Lagrangian relaxation heuristic with the application of cutting planes, given that it is a non-deterministic polynomial-time (NP) problem. The authors report reaching optimal solutions in most instances. In later work, Simrin *et al.* [28] study the DBAP which they solve using a linearization approach.

A second distinction can be made with respect to the layout of the quay. In the case of a discrete layout, the quay is partitioned and ships are subsequently assigned to a single berth. In the continuous layout, ships are positioned along the quay respecting physical limitations. One of the notable works in the field is that of [24], in which the authors study the discrete SBAP with an objective to minimize the waiting and handling time of a vessel. This is done under the assumption that the vessel berthing position and the QC operation schedule and rate are the main factors for determining the handling time. In another distinct work, Imai *et al.*, [15] provide a genetic algorithm to solve the discrete BAP with an objective function of minimizing the weighted number of vessel rejections; a vessel can be rejected from being berthed if it cannot be served without passing the due date, represented by the maximum waiting time. Alzaabi and Diabat [5] study the BAP with a special focus on vessel length considerations, adopting a hybrid layout setting of the quay, for more efficient utilization.

The BAP is frequently integrated with the Quay Crane Assignment Problem (QCAP). Each of [11, 15, 20] study this integration, of the discrete BAP with the QCAP, where the handling time depends on the number of quay cranes (QCs) assigned to the berthing vessels. Specifically, a certain number of QCs have to be assigned to each vessel in the model developed by [15]. Liang *et al.* [20] develop a formulation that aims to determine the berthing space, number of QCs and total handling time of each ship. Giallombardo *et al.* [11] develop what they call the Tactical Berth Allocation Problem (TBAP), which simultaneously assigns berths and cranes to incoming vessels. Tactical berth allocation was also considered by [13], where the objective aims to minimize the maximum crane capacity reservation. Also, the service time window, crane capacity and the quay length are reserved for vessels arriving periodically.

In some papers, the handling time of vessels in berth planning is estimated through QC assignment and QC scheduling; this is studied by [21] whose objective aims to minimize the maximum relative tardiness of vessels departure [7] study the integrated DBAP and QCAP which was developed based on a rolling-horizon approach. Lee *et al.* [18] study the continuous DBAP with the objective of minimizing the total weighted flow time. In their work, they propose an efficient method to address the problem by identifying possible vessel berth locations in the time-space diagram. Rodriguez-Molins *et al.* [26] propose a new model for the continuous DBAP that is integrated with the QCAP; the aim is to minimize the total waiting time elapsed to serve all vessels. A stochastic vessel arrival and handling time is considered by [32]. The objective of the research is to minimize the total departure delay and the length of the buffer time. The authors suggest that buffer times between berthed vessels increase the robustness of berth assignment.

So far, all presented works have studied several variants of the BAP for container terminals. Umang *et al.* [31] proposed the first berth allocation in the context of bulk ports. The hybrid and dynamic BAP formulation considers the cargo types assigned to vessels, as in this case the cargo is no longer transported in containers, and thus it is essential to take into account its type. The handling times are fixed components that depend on the available facilities and resources, such as the storage location based on cargo type, as well as the type of cranes required to load/discharge the cargo. The objective of the problem aims to minimize the total waiting and handling time of vessels.

As an extension to this first paper, Robenek *et al.* [25] integrated the hybrid and dynamic BAP with yard assignment in the context of bulk ports. These two crucial optimization problems were solved in a single large problem. Similar to the first one, the objective function of the problem aims to minimize the total waiting and service time of vessels berthed at the port. Several realistic assumptions were taken into consideration, strengthening the practicality of the developed model. These include dynamic ship arrival, draft considerations (water depth and ship draft), cargo handling capacity, storage location restrictions based on the type of cargo and congestion constraints. Furthermore, a hybrid berth layout is adopted, that combines both discrete and continuous layout characteristics, which increases berth utilization.

The formulation presented in the current paper is based on that of [25], with certain additional considerations. These include a cargo weight consideration, based on the fact that there are special berths for accommodating heavy-weight cargo. Furthermore, yard storage capacity is considered, in addition to the existing handling capacity constraints, in order to make sure resource capacity is not violated. We generate a number of cutting constraints, which are used to narrow the solution space. Finally, the current paper makes a practical contribution by presenting a case study on the bulk port operations of Mina Zayed, Abu Dhabi.

3. Problem description and formulation

In this section the problem characteristics and assumptions are presented in detail. Furthermore, the developed mathematical formulation is outlined and described thoroughly in the second part of the current section.

3.1. Problem description

For a set of N incoming vessels to be berthed at the port, indexed by i, the berthing problem will assign them to a set of available quay sections M, represented by index k. Since the model refers to bulk ports, each type of cargo must be explicitly considered among a set of cargo types, W. The integrated model ensures that each vessel i is assigned to the nearest available yard storage location from the set of yard locations P, represented by index p. Figure 1 is an illustration of a small instance of the bulk port layout with the yards. As shown in Figure 1, 2 vessels are being serviced in the 3 available berth sections, and the 3 available yard storage locations are assigned to 3 different cargo types (grain, iron ore, and coal).

Any vessel required to berth at the quay must occupy a number of berth sections determined by its own length and the length of the sections. The problem adopts a hybrid berth layout, a combination of both the discrete and continuous layout. The location of the yard(s) assigned to the vessel is very important because it determines the handling time. Hence, the closer the assigned yard is to the vessel berthing section, the less the traveling distance for the cargo, and thus the lower the handling time will be. The handling time of each vessel

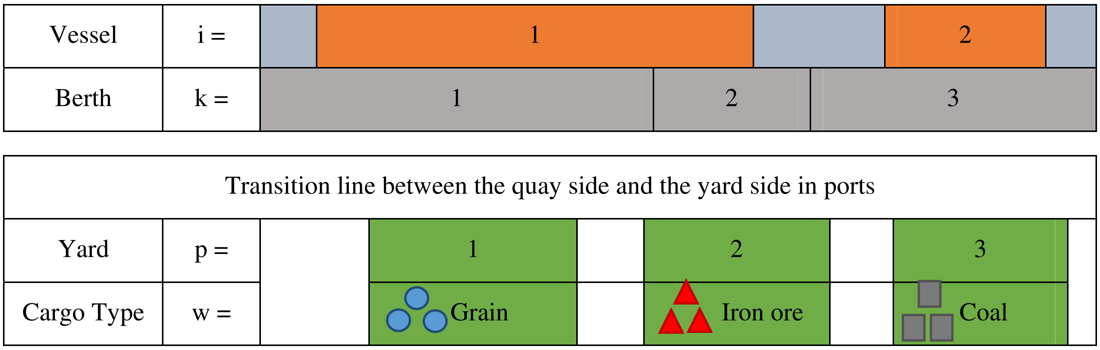

Figure 1. A layout diagram of bulk terminal.

is determined by several factors, including: the quantity of cargo, the number of assigned mobile cranes for bulk cargo, the rate of crane service (quantity/time), the number of specialized fixed facilities (if applicable), the transfer rate for each type of cargo, the travel distance for every type of cargo. There are several constraints applied to this model to ensure a feasible and realistic output. The following section presents the formulation in detail.

3.2. Problem formulation

To begin with, we present the notations used in the proposed formulation, which are as follows:

Parameters

N	Set of vessels i $(1, 2, \ldots, \lvert N\rvert)$.
M	Set of quay sections k $(1, 2, \ldots, \lvert M\rvert)$.
P	Set of storage locations p $(1, 2, \ldots, \lvert P\rvert)$.
W	Set of cargo types w (grain, clay, $\ldots$, $\lvert W\rvert$).
H	Set of time steps t $(1, 2, \ldots, \lvert H\rvert)$.
W_i	Cargo type to be loaded or discharged from vessel i.
$\bar{P}_{(p)}$	Set of cargo locations neighboring cargo location p.
$\bar{W}_{(w)}$	Set of cargo types that cannot be stored adjacent to cargo type w.
γ	Set of two-coupled corner berth sections k.
π	Set of heavy weight vessels i (Cargo Weight $\geqslant$10 000 tones).
σ_k	Set of sections k that cannot handle heavy weight cargo ($\geqslant$10 000 tones).
A_i	Arrival time of vessel i.
D_i	Draft of vessel i.
L_i	Length of vessel i.
Q_i	Quantity of cargo for vessel i.
d_k	Draft of section k.
l_k	Length of section k.
b_k	Starting coordinate of section k.
α_{ik}^{w}	Deterministic component of handling time for cargo type w of vessel i berthed at section k.
V_w	Constant that depends on the rate of transfer of cargo type w.
r_k^p	Distance between cargo location p and section k.
R_w	Maximum amount of cargo type w that can be handled in a single time step.
L	Total length of quay.
B	Large positive constant.
F	Maximum number of cargo locations that can be assigned to a single vessel.
φ_p	Maximum amount of cargo that can be stored at yard location p.
ρ_{ilk}	Fraction of cargo handled at section k when section l is the first section occupied by vessel i.
δ_{ilk}	1 if vessel i starting at section l touches section k, 0 otherwise.
ϑ_{ik}	1 if the facility required by vessel i is available at section k, 0 otherwise.
c_i	The total handling time of vessel $i \in N$.
h_{ik}^{w}	Handling time of a unit quantity of cargo type w of vessel i berthed at section k.
β_{ik}^{w}	Variable component of the handling time of vessel i with cargo type w berthed at section k along the quay.
e_k^i	Weighted average distance between section k occupied by vessel i and all cargo locations assigned to the vessel.

Decision variables

m_i	The starting time of handling of vessel $i \in N$.
q_{ip}	Amount of cargo handled by vessel i at cargo location p.

$$s_k^i \begin{cases} 1 \text{ if section } k \in M \text{ is the starting section of vessel } i \in N \\ 0 \text{ otherwise.} \end{cases}$$

$$x_{ik} \begin{cases} 1 \text{ if vessel } i \in N \text{ occupies section } k \in M \\ 0 \text{ otherwise.} \end{cases}$$

$$y_{ij} \begin{cases} 1 \text{ if vessel } i \in N \text{ is berthed to the left of vessel } j \in N \text{ without space overlap} \\ 0 \text{ otherwise.} \end{cases}$$

$$z_{ij} \begin{cases} 1 \text{ if handling of vessel } i \in N \text{ finishes before the start of handling of vessel } j \in N \\ 0 \text{ otherwise.} \end{cases}$$

$$\mu_p^w \begin{cases} 1 \text{ if cargo type } w \text{ is stored at cargo location } p \\ 0 \text{ otherwise.} \end{cases}$$

$$\emptyset_{ip} \begin{cases} 1 \text{ if cargo location } p \text{ is assigned to vessel } i \\ 0 \text{ otherwise.} \end{cases}$$

$$\theta_{it} \begin{cases} 1 \text{ if vessel } i \text{ is being handled at time } t \\ 0 \text{ otherwise.} \end{cases}$$

$$\omega_t^{ip} \begin{cases} 1 \text{ if vessel } i \text{ is being handled at location } p \text{ at time } t \\ 0 \text{ otherwise.} \end{cases}$$

The model is based on the one developed by [25], with additional realistic considerations pertaining to both the BAP and YAP. This section will discuss the development of the model, presenting the objective function and constraints in detail.

$$\text{Min} \sum_{i \in N} (m_i - A_i + c_i). \tag{1}$$

Subject to:

$$m_i - A_i \geqslant 0 \qquad \forall i \in N \tag{2}$$

$$\sum_{k \in M} \left(s_k^j b_k\right) + B(1 - y_{ij}) \geqslant \sum_{k \in M} \left(s_k^i b_k\right) + L_i \qquad \forall ij \in N, i \neq j \tag{3}$$

$$m_j + B\left(1 - z_{ij}\right) \geqslant m_i + c_i \qquad \forall i \in N, \forall j \in N, i \neq j \tag{4}$$

$$y_{ij} + y_{ji} + z_{ij} + z_{ji} \geqslant 1 \qquad \forall i \in N, \forall j \in N, i \neq j \tag{5}$$

$$y_{ij} + y_{ji} \leqslant 1 \qquad \forall i \in N, \forall j \in N, i \neq j \tag{6}$$

$$z_{ij} + z_{ji} \leqslant 1 \qquad \forall i \in N, \forall j \in N, i \neq j \tag{7}$$

$$\sum_{k \in M} s_k^i = 1 \qquad \forall i \in N \tag{8}$$

$$\sum_{k \in M} \left(s_k^i b_k\right) + L_i \leqslant L \qquad \forall i \in N \tag{9}$$

$$\sum_{l \in M} \left(\delta_{ilk} s_l^i\right) = x_{ik} \qquad \forall i \in N, \forall k \in M \tag{10}$$

$$x_{il} + x_{ik} \leqslant 1 \qquad \forall kl \in \gamma, l \neq k \tag{11}$$

$$\sum_{k\in M}\vartheta_{ik}X_{ik}\geqslant 1 \qquad \forall i\in N \tag{12}$$

$$\sum_{i\in\pi_i}x_{ik}=0 \qquad \forall k\in\sigma \tag{13}$$

$$(d_k-D_i)x_{ik}\geqslant 0 \qquad \forall i\in N,\ \forall k\in M \tag{14}$$

$$c_i\geqslant h_{ik}^{w}\rho_{ilk}Q_i-B(1-s_l^{i}) \qquad \forall i\in N,\ \forall l\in M,\ \forall k\in M, \forall w\in W_i \tag{15}$$

$$h_{ik}^{w}=\alpha_{ik}^{w}+\beta_{ik}^{w} \qquad \forall i\in N,\ \forall w\in W_i,\ \forall k\in M \tag{16}$$

$$\beta_{ik}^{w}=V_we_k^{i} \qquad \forall i\in N,\ \forall w\in W_i,\ \forall k\in M \tag{17}$$

$$e_k^{i}=\sum_{p\in P}(r_k^{p}q_{ip})/Q_i \qquad \forall i\in N,\ \forall k\in M \tag{18}$$

$$Q_i=\sum_{p\in P}q_{ip} \qquad \forall i\in N \tag{19}$$

$$q_{ip}\leqslant\emptyset_{ip}Q_i \qquad \forall i\in N,\ \forall p\in P \tag{20}$$

$$\emptyset_{ip}\leqslant q_{ip} \qquad \forall i\in N,\ \forall p\in P \tag{21}$$

$$q_{ip}\leqslant\sum_{w\in W_i}\sum_{t\in H}\Big(R_w\omega_t^{ip}+B\left(1-\mu_w^{p}\right)\Big) \qquad \forall i\in N,\forall p\in P \tag{22}$$

$$\sum_{p\in P}\emptyset_{ip}\leqslant F \qquad \forall i\in N \tag{23}$$

$$\sum_{i\in N}q_{ip}\leqslant\varphi_p \qquad \forall p\in P \tag{24}$$

$$\mu_w^{p}+\mu_{\bar w}^{\bar p}\leqslant 1 \qquad \forall w\in W_i,\forall\bar w\in\bar W_{(w)},\forall p\in P,\forall\bar p\in\bar P_{(p)} \tag{25}$$

$$\sum_{i\in N}\omega_t^{ip}\leqslant 1 \qquad \forall p\in P,\ \forall t\in H \tag{26}$$

$$\sum_{w\in W}\mu_w^{p}\leqslant 1 \qquad \forall p\in P \tag{27}$$

$$\emptyset_{ip}\leqslant\mu_w^{p} \qquad \forall i\in N,\ \forall w\in W_i,\ \forall p\in P \tag{28}$$

$$\omega_t^{ip}\geqslant\emptyset_{ip}+\theta_{it}-1 \qquad \forall i\in N,\ \forall p\in P,\ \forall t\in H \tag{29}$$

$$\omega_t^{ip}\leqslant\emptyset_{ip} \qquad \forall i\in N,\ \forall p\in P,\ \forall t\in H \tag{30}$$

$$\omega_t^{ip}\leqslant\theta_{it} \qquad \forall i\in N,\ \forall p\in P,\ \forall t\in H \tag{31}$$

$$\sum_{t\in H}\theta_{it}=c_i \qquad \forall i\in N \tag{32}$$

$$t+B\left(1-\theta_{it}\right)\geqslant m_i+1 \qquad \forall i\in N,\ \forall t\in H \tag{33}$$

$$t\leqslant m_i+c_i+B(1-\theta_{it}) \qquad \forall i\in N,\ \forall t\in H \tag{34}$$

$$s_k^{i}x_{ik}\in\{0,1\} \qquad \forall i\in N,\ \forall k\in M \tag{35}$$

$$y_{ij}z_{ij}\in\{0,1\} \qquad \forall ij\in N \tag{36}$$

$$\mu_w^{p}\in\{0,1\} \qquad \forall p\in P,\ \forall w\in W \tag{37}$$

$$\omega_t^{ip}\in\{0,1\} \qquad \forall i\in N,\ \forall p\in P,\ \forall t\in H \tag{38}$$

$$\emptyset_{ip}\in\{0,1\} \qquad \forall i\in N,\ \forall p\in P \tag{39}$$

$$\theta_{it}\in\{0,1\} \qquad \forall i\in N,\ \forall t\in H \tag{40}$$

$$m_i\geqslant 0 \qquad \forall i\in N,\ \forall p\in P.$$

The objective function of the model (1) aims to minimize the total service time of all vessels berthed at the port, within the specified planning horizon. The service time includes the waiting time and handling time for all vessels. Constraints (2) ensure the dynamic arrival process of vessels, while constraints (3)–(5) are the non-overlapping restriction constraints in the space-time diagram for any two vessels berthing at the port. In constraints (3) and (4) a large constant is introduced to ensure linearity. Constraints (6) and (7) are the cutting constraints, added to the model with the purpose of reducing the solution space, without altering the value of the optimal solution. Constraints (8)–(10) guarantee that each vessel can occupy more than one berth section, determined by its length and the starting section coordinate.

Constraints (11) are the corner restriction constraints, according to which a vessel cannot occupy two corner sections l and k simultaneously at any time. Constraints (12) determine whether the chosen berth section k supports the facility required by vessel i. Constraints (13) ensure that any vessel carrying heavy weight cargo will be berthed at the suitable locations. In order to ensure the vessel draft does not exceed the occupied berth section draft, constraints (14) are introduced. Constraints (15) determine the total handling time for any vessel; it is defined as the handling time of the occupied section with the latest completion time. The handling time per unit cargo is determined by the sum of a fixed and variable component, as represented by constraints (16). Constraints (17) determine the variable component of the handling time for vessel i berthed at section k, which is the product of the cargo transfer rate and the weighted average distance. The weighted average distance is defined as the weighted distance over the transferred cargo quantities between all cargo locations p assigned to vessel i berthing at section k, and it is determined by constraints (18). Constraints (19)–(21) ensure that the sum of all cargo quantities transferred to or from all cargo locations p are equal to the total cargo quantity to be loaded or discharged for vessel i. The capacity constraints (22) are introduced to ensure that the amount of cargo transferred does not exceed the allowed or the maximum amount of cargo which can be handled at any time. Highlighting R_w, its value may change depending on the mode of cargo transfer. For example, if the cargo is transferred using specialized fixed facilities like conveyors or pipelines, the value of R_w will be considered as the speed of conveyors or the flow rate of the pipelines. Where in all other case (auxiliary transfer equipment), R_w will be referred to as the maximum transfer rate for cargo between the quay and the yard sides; an example of such equipment are wheel loaders or loading shovels.

In order to consider the maximum (upper bound) number of cargo locations assigned to any vessel, constraints (23) are introduced. Constraints (24) ensure that the total amount of cargo stored at any yard storage area p does not exceed its capacity. Constraints (25) ensure that two different cargo types are not stored adjacently to avoid any intermixing, for example liquid clay, and coal cannot be stored next to one another. Constraints (26) ensure that a cargo location p must be assigned to one vessel at any time step to avoid any congestion. Constraints (27) ensure that yard locations are dedicated to cargo types, and only one cargo type can be assigned to a yard location at any time. Constraints (28) take into account the assignment of a vessel to a yard with the required cargo type. In other words, it prevents the assignment of a vessel to an empty yard or to a yard with the wrong cargo type.

Constraints (29)–(31) are introduced to control the value of ω_t^{ip} which must take a value of 1 if both binary variables θ_{it} and $\emptyset_{ip}$ are each equal to 1. The constraint indicates that a vessel i is assigned to a yard location p at a unit time t if and only if both following conditions are satisfied: vessel i is being handled at time step t and the yard location p is assigned to handle vessel i. Similarly, in order to control the value of the binary variable θ_{it}, constraints (32)–(34) are introduced. The value of θ_{it} should be equal to 1 at all time intervals between the starting time and the finishing time of handling vessel i, and 0 otherwise. Finally, constraints (35)–(40) are integrality constraints, which define the decision variables.

4. MINA ZAYED CASE STUDY

The current section examines the integrated BAP and YAP for the case of Mina Zayed Port, in Abu Dhabi, by means of an experimental analysis conducted using a combination of commercial software, namely

TABLE 1. Mina Zayed port characteristics

Location Lat./ Long	24°31’ 4” N - 54°23’ 0” E	Police office	Yes
Quay wall	3.7 m	Storage	143 000 m^2 of covered warehouse space 20 000 tons of cold storage
Quay Length	3450 m		
Pilotage	Available all time	Fuel availability	Yes
Admiralty chart number	3 713 3715 and 3177	Fresh water	Yes
Berth length	4372 m	AD customs	Yes
Type of cargo	General, liquid bulk, dry bulk, break bulk, Ro-Ro	Handling Equipment	Quay Cranes, Forklift and Tug master
VTS & ports control	Yes	Marine craft & services	Tugs, Pilot boats and Speed boats

GAMS-CPLEX. The section begins with a brief overview of the port of Mina Zayed, before moving on to the details of the experimental analysis.

4.1. Overview of Mina Zayed port

The port of Mina Zayed is operated by Abu Dhabi Ports (ADP), which is the port authority for all commercial ports in the emirate of Abu Dhabi. ADP is the master developer and manager of ports and industrial zones in the emirate, and it is expected to contribute to about 15% of non-oil GDP by 2030. This highlights the importance of ensuring efficient operations of its ports, in order to maximize throughput and support the emirate’s economy.

The port of Mina Zayed has constituted a main gateway for all cargo shipped to and from Abu Dhabi since its inauguration in 1972. Due to the launch of the semi-automated new port, namely Khalifa Port, in 2012, Mina Zayed is currently being re-organized as all its container traffic will now be handled by Khalifa Port, leaving Mina Zayed responsible for cargo shipment. The Mina Zayed area consists of three different basins, namely Mina Zayed, New Port and Free Port.

The current research focuses on the main basin, Mina Zayed. It includes 21 berths, which cover 510 hectares, providing 143 000 m^2 of warehouse space, along with a capacity of 20 000 tons of cold storage facilities. As container traffic is moved to Khalifa Port, Mina Zayed is still handling general cargo, breakage bulk cargo, dry bulk cargo and Ro-Ro. General specifications of Mina Zayed are provided in Table 1.

The quay side and yard side of Mina Zayed contain a wide range of vessel- and shipment-handling equipment, including 14 quay cranes aligned on a rail, 6 rail mounted gantries which are used for container shuffling and one mobile crane with a capacity of 150 tons. On the other hand, the port operations are enabled by 90 fork lift trucks that can handle cargo of up to 32 tons, 13 straddle carriers, 13 empty container handlers, 54 terminal tractors, and 100 terminal trailers.

4.2. Experimental study on Mina Zayed port

The strengthened formulation presented in Section 3 is implemented on the case of Mina Zayed. The scope of the current analysis is to use the data acquired from the port operator, with the aim of providing insight on the actual operations, identifying factors that impact operations and suggesting recommendations for potentially improved resource utilization. The data includes the list of all vessels that were berthed at the port during the three first months of 2014. Also, the data specifies which vessels carried Ro-Ro, general and bulk cargo, as these types are the main focus of the case study. The data includes vessel length, draft, arrival time, cargo type, cargo quantity in terms of volume and weight as well as the port layout related data. The latter is summarized in Table 2.

The data was sorted by dividing the vessels into groups of 17 (equal to the number of berths), without changing their arrival order, leading to a total of 8 groups of 17 handled vessels each. This distinction was necessary in order to ensure solvability by CPLEX. The order of the arrival time for each group was determined by the given arrival date and time, with respect to the last day of the last arriving vessels in the group. Regarding

Table 2. Distances in m between berths and yards of Mina Zayed port.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1132	1338	1363	1411	1910	2068	2251	2433	2738	2251	4234	4417	4660	4842	5025	5451
2	888	1071	1156	1144	1643	1801	1983	2166	2470	1983	3966	4149	4392	4575	4757	5183
3	535	767	864	852	1363	1521	1703	1886	2190	1703	3687	3869	4112	4295	4477	4903
4	718	402	645	767	1144	1302	1484	1667	1971	1484	3468	3650	3893	4076	4258	4684
5	1022	535	377	1071	864	1022	1205	1387	1691	1205	3188	3370	3735	3796	3979	4404
6	1278	779	511	1302	998	1156	1338	1521	1825	1338	3322	3504	3747	3930	4112	4538
7	2336	1959	1630	1740	900	779	706	961	1265	779	2738	2920	3163	3346	3528	3954
8	2178	1801	1472	1582	961	840	767	803	1107	621	2579	2762	3005	3188	3370	3796
9	2251	1874	1545	1655	1034	913	840	876	1180	694	2652	2835	3078	3261	3443	3869
10	2531	2154	1825	1935	1095	937	754	572	694	973	2129	2312	2555	2738	2920	3346
11	2567	2190	1862	1971	1132	973	791	608	730	1010	2166	2348	2592	2774	2957	3382
12	3735	3358	3030	3139	2397	2239	2056	1874	1995	2275	681	864	1107	1290	1472	1898
13	4173	3796	3468	3577	2835	2677	2494	2312	2433	2713	742	681	1010	1217	1460	1886
14	4429	4052	3723	3833	3090	2932	2750	2567	2689	2969	1034	852	791	986	1180	1643
15	4477	4100	3772	3881	3139	2981	2798	2616	2738	3017	1083	900	840	1034	1229	1691
16	4672	4295	3966	4076	3334	3176	2993	2932	2932	3212	1253	1095	827	815	316	365
17	4855	4477	4149	4258	3516	3358	3176	2993	3115	3395	1399	1278	1022	827	377	183

the cargo unit quantity used by the model, we assumed that for general and bulk cargo it is equal to 1 unit, while for Ro-Ro, it is equal to 100 vehicles.

The structure of the experiment is as follows: the data acquired corresponds to the scenario that is titled "Base Case". Further, three scenarios are considered and discussed: "Congestion", "Closing" and "Adding". The first scenario tests the operations when an increase in the number of arriving vessels occurs, thus leading to higher congestion. The second scenario tests the sensitivity of operational efficiency with respect to certain resources becoming unavailable, due to sudden breakdown or maintenance works. Finally, the third scenario tests the case of adding resources to accommodate the number of vessels. For each scenario, a set of instances are tested and compared to each other and to the Base Case.

A set of restrictions is normally imposed by the port operator, and these were taken into account in the current experimental process. As shown in Figure 2, the blue yard storage space is dedicated to Ro-Ro units, while the green and pink yards can accommodate any type of general and dry bulk cargo; sometimes the green yard can hold Ro-Ro, if required. However, grains and oil that require special facilities have their own dedicated storage yards.

The instances generated for the experimental analysis are grouped according to scenarios. For the "congestion" scenario, four cases were introduced with a different congestion level determined by the mean value. The level of congestion was generated for each of the four scenarios using a normal distribution, with a mean equal to 10, 8, 5 and 2 and with a standard deviation of 5, respectively. These numbers correspond to the vessels' arrival times. The smaller the mean, the more congested the port will be, as vessels' arrival times are much closer to one another.

In the "closing" scenario, the instances are grouped based on berths and yards. The berth closing instances are introduced for every 500 m of the total port quay line. For yard closing instances, 50% of the available yards are shut off for the 3 main groups (blue, green and pink) in order to test which group is most sensitive to becoming unavailable.

Finally, regarding the "adding" scenario, it also has to do with berths and yards. In this case, the instances are designed to be consistent with the real case. Specifically, the added berth sections are assumed at real possible positions, rather than imaginary ones; this is similarly done for yards. Also, a combination of adding both berths and yards is necessary to determine the combined effectiveness of additional resources.

Figure 2. Layout of Mina Zayed basin.

As mentioned, the experimental analysis was conducted using GAMS-CPLEX, specifically GAMS version 24.3.1 and CPLEX version 12.5, on a Dell workstation with Intel® Core™ i5 2540M CPU @2.60GHz processors with Windows 7 operating system. Each group in the experiment contains up to 17 vessels, equal to the number of available berths, but also due to the fact that CPLEX could not give optimal solutions within reasonable time for 20 or more vessels. Although the maximum optimality gap was set to be 2%, the computational time remains significant for some instances. While most instances run in seconds, some took as much as days, in which case the CPU time was denoted by a dash (–). The results were then plotted for a visual representation. Of the 8 groups tested, the 4 most useful in terms of results are presented in this section. Note that the groups correspond to a set of vessels, based on data received by the port operator. The analysis is thus summarized in the following tables and figures. To begin with, Table 3 summarizes the characteristics of the various scenarios.

Group 1

Table 4 demonstrates the results obtained from running the instances of group 1. As shown in Figure 3, the congestion instances (group A) showed a clear effect on the total service time of vessels. Congestion increased service time, except in the case of instance A3 in which service time decreased slightly with comparison to A2. This is due to the shorter interarrival times of vessels, which allows the solver to shuffle the sequence of vessels and find the one that should be berthed first, from a time-efficiency perspective.

The results obtained from the closing scenario are shown in Figure 4; the graph shows that there are no effects of closing every 500 m of the port's quay line and this is mainly due to the length range of the vessels and the length range of the berth sections. The average length of the vessels is 184 m which is less than the average length of the quay berths (203 m). Also, the central yards are the most sensitive to any disturbance in operation, but this does not correspond to an increase in total service time. Moreover, adding resources is not particularly effective in terms of decreasing service time, except for the case of instance D2, as depicted

Table 3. Summary and description of scenarios

Instance	Scenario	Description
Base	None	Base case
A1	Congestion	Arrival with mean value of 10 days
A2	Congestion	Arrival with mean value of 8 days
A3	Congestion	Arrival with mean value of 5 days
A4	Congestion	Arrival with mean value of 2 days
B1	Closing	Close 500 m of berth (1)
B2	Closing	Close 500 m of berth (2)
B3	Closing	Close 500 m of berth (3)
B4	Closing	Close 500 m of berth (4)
B5	Closing	Close 500 m of berth (5)
B6	Closing	Close 500 m of berth (6)
C1	Closing	Close 50% of south yards (Blue)
C2	Closing	Close 50% of central yards (Green)
C3	Closing	Close 50% of north yards (Pink)
D1	Adding	Add new berths (construct)
D2	Adding	Add new berths and yards (construct)
D3	Adding	Add new yards in north (construct)
E1	Adding	Increase berth sections to 27
E2	Adding	Increase yard areas to 21

Table 4. Results of Group 1.

	MILP-CPLEX				MILP-CPLEX		
Instance	Objective value (day)	Gap (%)	CPU Time (s)	Instance	Objective value (day)	Gap (%)	CPU Time (s)
Base	39.42	1.62	1.89	B6	39.43	0.02	3.65
A1	41.13	1.91	2.14	C1	39.42	1.9	2.26
A2	41.23	0.81	6.96	C2	40.21	1.9	4.01
A3	41.14	1.8	8.72	C3	39.42	1.4	1.58
A4	43.30	9.7	–				
				D1	39.42	1.9	3.93
B1	39.42	1.8	4.38	D2	38.42	1.69	11.11
B2	39.42	1.99	3.63	D3	39.42	1.59	13.81
B3	39.42	0.86	2.18				
B4	39.42	1.5	2.34	E1	39.55	0.7	1.97
B5	39.45	1.5	1.48	E2	39.42	1.5	12.67

by Figure 5. However, the scenario of increasing the berths of Mina Zayed port to 27 berth sections (Instance E1) shows a very slight increase in the total service time, yet not significant.

Group 2

The results of the generated instance of group 2 are shown in Table 5. As shown, the computational time for all runs is less than 10 s which means that the parameters entered for this group are very effective and therefore it can be used as a benchmark case. The instances of the congestion loop illustrated in Figure 6 show a significant change in the total service time as congestion increases. Instance A1 does not show any change compared to the base case and that is because the vessels' interarrival time ranges for both instances remain the same. The trend for the congestion scenarios is consistent with expectation.

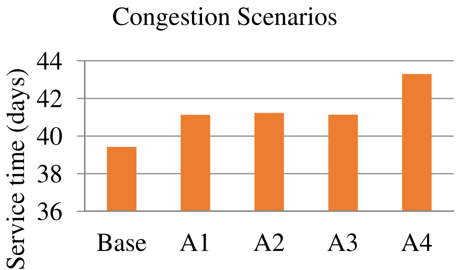

Figure 3.

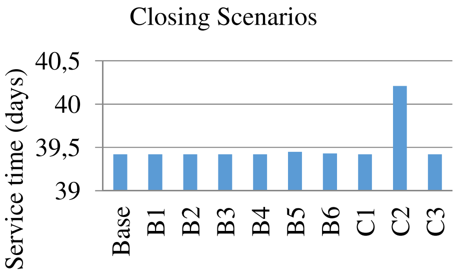

Figure 4.

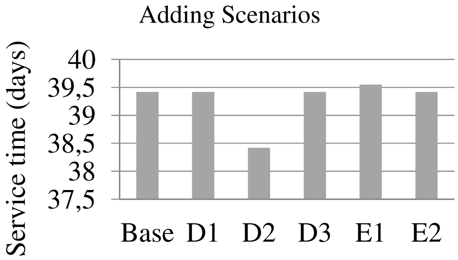

Figure 5.

Table 5. Results of Group 2.

	MILP-CPLEX				MILP-CPLEX		
Instance	Objective value (day)	Gap (%)	CPU Time (s)	Instance	Objective value (day)	Gap (%)	CPU time (s)
Base	29	0	5.04	B6	29	1.9	5.41
A1	29	0	5.29	C1	29	0	1.37
A2	29.58	1.9	5.83	C2	29.55	1.8	1.75
A3	30.01	1.6	5.93	C3	29	0	0.94
A4	31.36	1.9	498.97				
				D1	29	0	8.28
B1	29	0	4.99	D2	28	0	8.02
B2	29	0	7.39	D3	29	0.1	14.16
B3	29	1.7	13.92				
B4	29.16	1.9	4.43	E1	29	0	8.67
B5	29.3	1	3.37	E2	28.56	1.9	5.71

Moving to the effects of the closing loop, the results in Figure 7 illustrate that the total service time does not change for most of the cases of closing every 500 m of the total quay line. However, instances B4 and B5 note an increase in the total service time indicating that the berth Sections 7–11 are the most sensitive berths along the quay line. Moreover, the closing of 50% of the central yard area caused a clear increase in the service time and this is potentially due to the high number of vessels requiring bulk cargo in this group. Figure 8

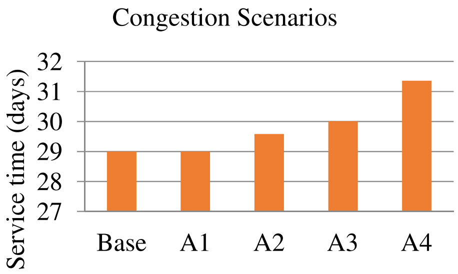

Figure 6.

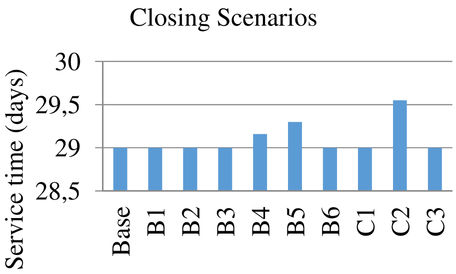

Figure 7.

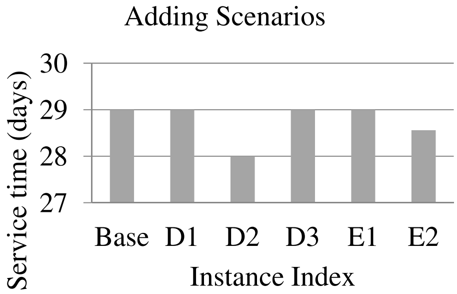

Figure 8.

Table 6. Results of Group 3.

	MILP-CPLEX				MILP-CPLEX		
Instance	Objective value (day)	Gap (%)	CPU time (s)	Instance	Objective value (day)	Gap (%)	CPU time (s)
Base	32.64	32.04	1.17	B6	32.64	0	3.04
A1	35.69	1.98	3.63	C1	32.64	1.7	1.31
A2	38.45	0.36	3.62	C2	32.64	1.7	0.98
A3	37.8	0.8	6.65	C3	32.64	1.8	3.54
A4	37.51	2	3975.76				
				D1	32.64	1.7	3.67
B1	32.64	1.83	1.45	D2	32.64	1.8	6.52
B2	32.64	0	2.18	D3	32.64	1.9	8.75
B3	33.04	1.2	2.12				
B4	32.64	1.8	3.03	E1	32.87	0.6	4.71
B5	32.64	1.97	3.82	E2	32.64	1.9	5.02

shows that the instances D2 and E2, corresponding to additional berths and yards and additional yards only, respectively, positively impact the total service time.

Group 3

This group exhibits the strangest results among all tested groups. As shown in Table 6, results are similar, with the exception of the congestion case. Therefore, it is not possible to extract reliable conclusions from this group. Figure 9 depicts odd behavior with respect to the effect of congestion on total service time. Surprisingly, instance A2 service time increases rapidly to the highest value among all instances. Also, service time seems

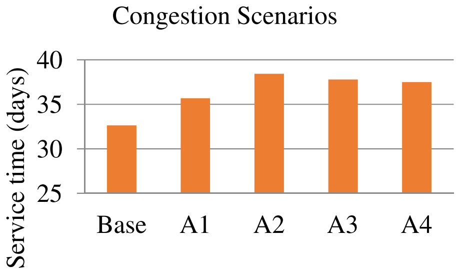

FIGURE 9.

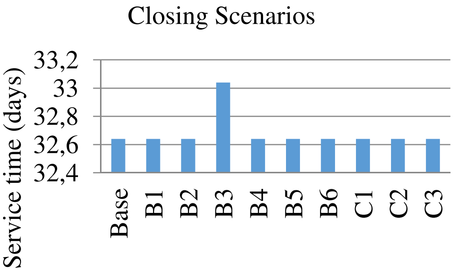

FIGURE 10.

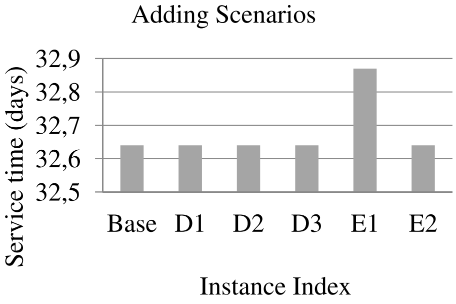

FIGURE 11.

to decrease with the increase of congestion. This implies that the parameters of this group are not effective and cannot be used for comparison.

Group 4

The results of this group are intuitive, as opposed to those obtained from testing the previous groups. The computational time varies greatly, which is also expected since the BAP is N-P hard [16]. The combination of the current parameters and congestion instances shows a certain dynamic, illustrated in Figure 12, according to which only A1 exhibits odd behavior, due to the difference between all arrivals following a normal distribution within the time range. In certain instances, such as A4 the results show that congestion caused a delay of around 3 days. Figure 13 shows a decrease in service time in certain instances, such as B1, B2 and B3. This may be due to the high average length of vessels that is equal to 182 m. Instance B5 is the one which proves most sensitive amongst the berth closing instances, followed by B4. Instance C2 (central yards) is the most sensitive instance among the yard instances and it is the most sensitive case in all closing instances. In Figure 14, once again instance D2 is the most effective compared to all adding instances, which is a result of the short travel space in the port.

Overall, the results obtained draw a clear conclusion of the effect of congestion, removal and addition of resources on the service time. It was observed that most instances in the various groups reached a near-optimal solution, with a gap less than 2%. Furthermore, the computational time was low, mainly due to the selection of a daily rather than hourly time step. Although this may not provide accurate results, it gives a satisfactory indication.

In the congestion loop instances, the total service time was expected to increase with congestion, and this is what happened in most cases, with the exception of a few instances. This can be attributed to the optimality gap. The length of vessels, cargo type, and cargo quantity along with the difference between vessels' interarrival times are the main contributors in determining the effects on the total service time. Moving on to the "closing"

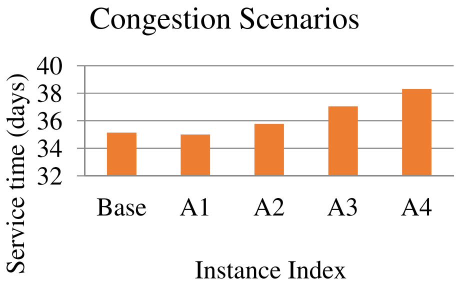

FIGURE 12.

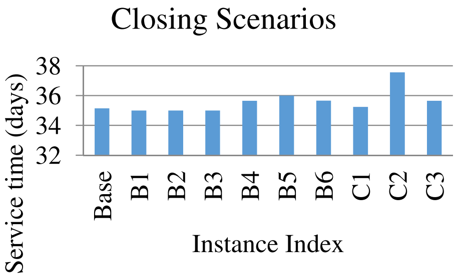

FIGURE 13.

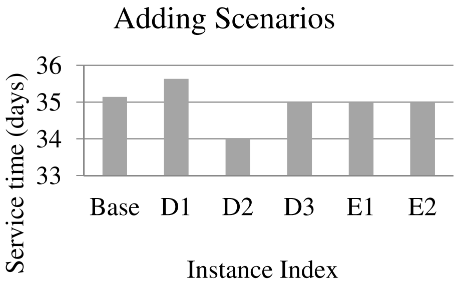

FIGURE 14.

TABLE 7. Results of Group 4.

MILP-CPLEX				MILP-CPLEX			
Instance	Objective value (day)	Gap (%)	CPU time (s)	Instance	Objective value (day)	Gap (%)	CPU time (s)
Base	35.14	0.85	14.96	B6	35.66	1.8	23.28
A1	35	0	24.23	C1	35.24	0.07	188.7
A2	35.77	1.99	171.9	C2	37.56	1.99	390.38
A3	37.05	1.99	3369.54	C3	35.65	1.97	78.7
A4	38.3	4.71	58 390				
				D1	35.63	1.77	25.86
B1	35	0	28.02	D2	34	1.98	56.96
B2	35	1.74	23.49	D3	35	1.98	35.4
B3	35	1.1	30.51				
B4	35.65	1.83	31.67	E1	35	0	23.95
B5	36	0.69	17.63	E2	35	1.22	28.72

scenario, drawing a solid conclusion was not straightforward, due to the odd behavior of certain results. The only clear point was that instances B4 and B5 were most sensitive and always demonstrated an increase; therefore, they must be considered more than the others in any case of closure. Similarly, the central yards (instance C2) are most sensitive to the addition of resources, and that is because their location is strategic for vessels carrying bulk cargo. The results of the instances generated for the adding loop show that there is no use in adding new berths to the best available location without adding new yard areas nearby. This is mainly due to the long travel distance between the new sections and other yards, creating further traffic congestion. Hence, adding only berths is not an effective strategy.

5. Conclusion

The current paper presents a formulation for the integrated Berth Allocation and Yard Assignment Problem (BYAP) in the context of bulk ports, which has not been addressed extensively in the literature, contrary to the respective problem in container terminal management. Integrating these two decisions in bulk ports can lead to improved operational planning, as more information is exploited that can reduce the time required to handle cargo ships. For example, the berth position assigned to a certain ship will change if there is information regarding the type of cargo and the respective location it will be transported to. It focuses on extending an existing formulation from the literature to account for further considerations in order to render the model even more realistic. The extended formulation is presented and explained in detail.

Furthermore, a case study is examined for the Mina Zayed Port of Abu Dhabi. Input data acquired through the port operator of Mina Zayed is implemented in the developed formulation, and different scenarios are tested as a means of a sensitivity analysis with respect to certain factors. These include the level of congestion, in terms of vessels' relative arrival times, the unavailability of certain resources and the addition of new resources. The impact of these factors on the service time is evaluated and the main findings dictate that the length of vessels, cargo type, and cargo quantity along with the difference between vessels' arrival times are the main contributors in determining the effects on the total service time. Another important conclusion is that additional berths do not increase port efficiency if not accompanied by additional yard storage space.

Future research can focus on developing a customized heuristic solution technique for the proposed formulation, in order to solve the problem in a time-efficient manner, providing near-optimal or optimal results. The importance of time-efficiency in such operations is crucial and it can largely determine the overall usefulness of the method as a means of improving operations at bulk ports.

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