Jurnal Teknik Industri, Vol. 27, No. 1, June 2025
ISSN 1411-2485 print / ISSN 2087-7439 online
DOI: https://doi.org/10.9744/jti.27.1.77-92

Optimizing Ship Berthing Allocation Strategies at a Dry Bulk Fertilizer Terminal: A Simulation Approach Considering Material Handling Equipment Availability

Maulin Masyito Putri[1*], Prita Meilanitasari[1], Nindya Putri Prasodjo[1], Dwi Sekar Arumjani[1]
[1)] Department of Logistics Engineering, Universitas Internasional Semen Indonesia
Kompleks PT. Semen Indonesia (Persero) Tbk, Gresik, East Java 61122, Indonesia
Email: maulin.putri@uisi.ac.id[1], prita.meilanitasari@uisi.ac.id[1], nindya.prasodjo20@student.uisi.ac.id[1], dwi.arumjani21@student.uisi.ac.id[1]
*Corresponding author

Abstract: Long loading and unloading times at ports lead to demurrage costs, which occur when these activities exceed the agreed time. Demurrage is a penalty paid by shippers or charters to ship owners for delays. These delays can be caused by factors such as a lack of available docks or unprepared material handling equipment. This study examines dry bulk ports, focusing on four types of material handling, each with distinct characteristics and functions: the Continuous Ship Unloader (CSU) and Kangaroo Crane (KC) for unloading, and the Vessel Crane Flat Truck (VCFT), New Ship Unloader (NSL), and Vessel Crane with Dump Truck (VCDT) for loading. The CSU is the primary equipment for unloading, while the NSL is prioritized for loading bulk cargo. The variety of equipment and cargo adds complexity, best addressed through a discrete simulation approach. The study aims to identify the optimal berth allocation scenario, reducing loading and unloading times, waiting times, and demurrage costs using a discrete event simulation approach. Improvement scenario 2, which assigns berths based on the material being handled, resulted in a 33.49% increase in unloading revenue, a 1.81% increase in loading revenue, and a 13.54% reduction in demurrage costs.

Keywords: Demurrage costs, material handling, dry bulk cargo, berth allocation, discrete event simulation.

Introduction

Dry bulk cargo terminals must swiftly adapt to the evolving dynamics of global supply chains [1]. The processes of loading and unloading, conveying, horizontal transport, and temporary storage involve intricate organizational structures and complex procedures that require constant adjustment to changing conditions. Rapid technological advancements, fluctuating trade volumes, and environmental constraints require terminals to implement adaptive, real-time management strategies to maintain efficiency and ensure sustainability in their operations. The most essential types of dry bulk terminals include raw materials and fertilizer products, which are crucial to many industrial and agricultural supply chains globally. Fertilizer terminals are vital to support global food production, as they handle the distribution of nutrients necessary for crops. As demand for raw materials and agricultural products continues to grow in many parts of the world, the role of dry bulk terminals remains critical for ensuring the smooth flow of goods across international supply chains. Optimizing loading and unloading operations at dry bulk terminals is crucial for minimizing delays and preventing additional costs like demurrage. Effective scheduling, efficient use of material handling equipment, and precise berth allocation help to ensure that ships complete their loading and unloading activities within the agreed time. By reducing idle time, operational bottlenecks, and unnecessary downtime, terminals can significantly improve turnaround times, thereby avoiding the penalties associated with exceeding laytime, known as demurrage. Demurrage is a key challenge in improving productivity and managing profit and loss in terminal operations. It represents a penalty or compensation paid to shipping companies when a vessel fails to load or discharge cargo within the agreed-upon timeframe, known as laytime [2]. Proper planning, improved coordination, and efficient resource allocation are essential to minimize demurrage costs, thus enhancing operational efficiency and terminal performance.

At dry bulk cargo terminals, a variety of material handling equipment is utilized to accommodate the diverse needs of cargo types and vessels. For unloading operations, equipment such as the Continuous Ship Unloader (CSU) and Kangaroo Crane (KC) are employed to handle bulk materials like Phosphate Rock (P-Rock), Muriate of Potash (MOP), Ammonium Sulfate (ZA), and sulfur. These machines are often integrated with conveyor systems, allowing efficient transfer of materials from the dock to storage facilities. However, in cases where conveyor systems are unavailable or unsuitable, the KC can also be paired with trucks for material distribution to inaccessible warehouses. When the CSU or KC is out of service or unable to operate, heavy equipment is brought in to ensure uninterrupted unloading operations. This flexibility is vital for maintaining terminal efficiency and avoiding delays that could lead to demurrage costs. The ability to seamlessly switch between equipment types minimizes disruptions, ensuring the cargo flow continues, even in the face of equipment downtime or failures. By leveraging such equipment diversity and operational adaptability, dry bulk terminals optimize productivity, reduce wait times, and enhance overall performance.

For loading operations, the port utilizes a range of specialized equipment, including the Vessel Crane Flat Truck (VCFT), New Ship Unloader (NSL), and Vessel Crane with Dump Truck (VCDT). The selection of equipment is tailored to the specific type of cargo being handled. Notably, bagged materials, which account for over 50% of the total cargo volume, are predominantly loaded using the VCFT. For bulk materials, the NSL is the primary choice due to its ability to service vessels moored both inside and outside the pier. In instances where the NSL is unavailable, the VCDT serves as an effective backup. Additionally, both the NSL and VCDT can operate simultaneously for a single vessel, enhancing efficiency. Terminals do not always have heavy equipment. They choose to rent heavy equipment for the loading and unloading process. To reduce rental costs, dry bulk terminals strive to minimize their reliance on heavy equipment.

The complexity of material handling operations at dry bulk cargo terminals, characterized by diverse equipment and cargo types, introduces a level of operational intricacy that is not present in ports with more uniform systems. Effectively managing these complexities necessitates meticulous planning around the Expected Time of Arrival (ETA) of vessels, which informs berth allocation and material handling assignments. Each pier is designed with varying depths to accommodate the deadweight tonnage (DWT) of incoming vessels. By carefully coordinating ship services based on ETA, material handling availability, and dock capacity, ports can significantly reduce both vessel waiting and unloading times, resulting in substantial savings in demurrage costs.

Research on material handling operations at ports has been extensively conducted using heuristic and simulation approaches [3], [4], [5], [6]. One notable study focuses on the operational strategy model for twin automatic stacking cranes in container yards at container ports, which was developed using a heuristic approach aimed at minimizing travel time and energy costs[7] . The discrete-event simulation can analyze the impact of congestion management initiatives, perform scenario analysis, assess terminal performance, improve understanding of terminal dynamics, and support decision-making by identifying the most effective congestion mitigation strategies[8]. The discrete-event simulation can assess various congestion management strategies at a container terminal by evaluating their impact on request completion time, equipment waiting time, and overall operational efficiency, helping identify the optimal configuration to enhance terminal performance[9].

Loading and unloading activities function as dynamic systems that allow for the observation of changes resulting from the implementation of specific policies. These systems incorporate continuous feedback loops, enabling adaptability to various scenarios. To simplify the analysis of such a complex system, a discrete simulation model has been developed to represent the loading and unloading operations at dry bulk cargo terminals. This simulation model is particularly valuable for addressing industrial challenges, as it facilitates the testing of multiple improvement scenarios without disrupting daily operational performance.

This study is highly complex due to the diverse material handling processes involved in both unloading and loading operations. For unloading, CSU I, CSU II, KC I, and KC II was utilized, while for loading, VCFT was used for bagged cargo, and NSL and VCDT were employed for bulk cargo. Beyond material handling at the pier, this research also considered transportation modes for moving cargo between the warehouse and the pier, such as conveyors, flat trucks, and dump trucks. The selection of the appropriate pier was based on factors including the vessel's Length Overall (LOA), cargo type, and cargo capacity. To solve the berth allocation problem, this study used discrete event simulation.

Methods

Berth Allocation Problem

Berth Allocation, Quay Crane Assignment and Quay Crane Scheduling Problem is classified as an NP-hard combinatorial optimization problem[10][11]. The following mathematical model formulates the Berth Allocation

Problem (BAP) based on the approach proposed by Malekahmadi[10], considering several assumptions. It assumes that identical cranes with a known work rate can serve any vessel, moving one container at a time horizontally without crossing each other and while maintaining a safe distance. Cranes remain assigned to a vessel's bay until the work is completed before moving to another bay, with negligible cost and time for crane movements. Vessel arrival times, quay length, vessel dimensions, and tidal conditions are known, where deep-draft vessels are restricted during low tides. The berthing space is continuous, allowing flexible vessel placement, and the planning horizon consists of equal time periods. Additionally, the number of cranes assigned to a vessel can vary over time.

Sets and Parameters

K: set of vessels
J_k: set of bays of the vessel k
Q: set of quay cranes
T: set of available temporal units
U: set of available spatial units in the berthing space
G: total length of the berthing space
$|J_k|$: number of bays of the vessel k
a_k: arrival time of the vessel k
s: safe distance between cranes
p_{kj}: number of containers in the bay j of the vessel k
c_k:cost of waiting and handling time of vessel k (per unit time)
d_{kut}: $\begin{cases} 1, \text{ if the vessel, quay, and tide conditions allow the vessel } k \text{ to dock at the position } u \text{ at the time } t \\ 0, otherwise \end{cases}$
M:a very large number

Decision Variables

x_{kjqt}: $\begin{cases} 1, \text{ if at the time } t \text{ the crane } q \text{ works on the bay } j \text{ of the vessel } k \\ 0, \text{ otherwise} \end{cases}$
v_{kjt}: $\begin{cases} 1, \text{ if at the time } t \text{ the work in the bay } j \text{ of the vessel } k \text{ is finished} \\ 0, \text{ otherwise} \end{cases}$
r_{kt}: $\begin{cases} 1, \text{ if at the time } t \text{ all the work on the vessel } k \text{ is finished} \\ 0, \text{ otherwise} \end{cases}$

y_{kt}: $\begin{cases} 1, \text{ if at the time } t \text{ the vessel } k \text{ is docked in the quay} \\ 0, \text{ otherwise} \end{cases}$
α_{kw}: $\begin{cases} 1, \text{ if the vessel } k \text{ arrives before the vessel } w \\ 0, \text{ otherwise} \end{cases}$
f_k: finishing time of work for the vessel k
l_k:location of the first bay the vessel k on the quay
ll_{kj}:location of the j^{th}bay the vessel k
lc_{qt}:location of the crane q on the quay at the time t
o_{kut}: $\begin{cases} 1, \text{ if at the time } t \text{ the vessel } k \text{ is docked in the position } u \text{ of the quay} \\ 0, \text{ otherwise} \end{cases}$

$$Min \sum_{k\in K} c_k(f_k - a_k + 1)$$
$$\sum_{k\in K}\sum_{j\in J_k} x_{kjqt} \le 1; \qquad \forall q \in Q, \forall t \in T$$
$$\sum_{q\in Q} x_{kjqt} \le 1; \qquad \forall k \in K, \forall j \in J_k, \forall t \in T$$
$$\sum_{q\in Q}\sum_{h=1}^{t} x_{kjqh} \ge p_{kj}v_{kjt}; \qquad \forall k \in K, \forall j \in J_k, \forall t \in T$$
$$\sum_{q\in Q}\sum_{t\in T} x_{kjqt} \le P_{kj}; \qquad \forall k \in K, \forall j \in J_k$$
$$x_{kjqt} \le x_{kjq,t+1} + v_{kjt}; \qquad \forall k \in K, \forall j \in J_k, \forall q \in Q, \forall t \in T, t \ne 1$$
$$v_{kjt} \ge r_{kt}; \qquad \forall k \in K, \forall j \in J_k, \forall t \in T$$

$$f_k = |T| - \sum_{t \in T} r_{k,t} + 1\,; \qquad \forall k \in K$$
$$\sum_{t \in T} r_{kt} \geq 1; \qquad \forall k \in K$$
$$\sum_{t < a_k} y_{kt} \leq 0; \qquad \forall k \in K$$
$$\sum_{q \in Q} x_{kjqt} \leq y_{kt}; \qquad \forall k \in K, j \in J_k, \forall t \in T$$
$$y_{kt} \leq y_{k,t+1} + r_{k,t+1}; \qquad \forall k \in K, \forall t \in T, t \neq |T|$$
$$y_{k,t+1} < 1 - r_{kt}; \qquad \forall k \in K, \forall t \in T, t \neq |T|$$
$$l_k + |J_k| - 1 \leq G; \qquad \forall k \in K$$
$$\alpha_{kw} + \alpha_{wk} = 1; \qquad \forall k, w \in K, k \neq w$$
$$l_k + |J_k| \leq l_w + M(1 - \alpha_{kw}) + M(1 - y_{kt}) + M(1 - y_{wt}); \qquad \forall k, w \in K, k \neq w, \forall t \in T$$
$$ll_{kj} = l_k + j - 1; \qquad \forall k \in K, \forall j \in J_k$$
$$lc_{qt} \leq ll_{kj} + M\left(1 - x_{kjqt}\right); \qquad \forall k \in K, \forall j \in J_k, \forall q \in Q, \forall t \in T$$
$$lc_{qt} \geq ll_{kj} - M\left(1 - x_{kjqt}\right); \qquad \forall k \in K, \forall j \in J_k, \forall q \in Q, \forall t \in T$$
$$lc_{qt} \leq G; \quad \forall q \in Q, \qquad \forall t \in T$$
$$lc_{qt} \geq 1; \quad \forall q \in Q, \qquad \forall t \in T$$
$$lc_{qt} \leq lc_{q+1,t} - s; \qquad \forall k \in K, \forall t \in T$$
$$y_{kt} \leq \sum_{u \in U} o_{kut}\,; \qquad \forall k \in K, \forall t \in T$$
$$o_{kut} \leq y_{kt}; \qquad \forall k \in K, \forall u \in U, \forall t \in T$$
$$o_{kut} \leq d_{kut}; \qquad \forall k \in K, \forall u \in U, \forall t \in T$$
$$l_k \leq u + M(1 - o_{kut}); \qquad \forall k \in K, \forall u \in U, \forall t \in T$$
$$l_k \leq u - M(1 - o_{kut}); \qquad \forall k \in K, \forall u \in U, \forall t \in T$$
$$l_k, ll_{kj}, lc_{qt}, s_k, f_k \geq 0; \qquad \forall k \in K, \forall j \in J_k, \forall q \in Q, \forall t \in T$$
$$x_{kjqt}, v_{kjt}, r_{kt}, y_{kt}, o_{kut}, \alpha_{wk} \in \{0,1\}; \qquad \forall k \in K, \forall j \in J_k, \forall q \in Q, \forall t \in T$$

The objective of the model is to minimize the total time from a vessel's arrival near the shore to its departure from the quay, encompassing both waiting time before berthing and handling time. Constraint (2) ensures that each bay of a vessel is assigned to only one crane at any given time, while Constraint (3) guarantees that a crane is not allocated to more than one bay simultaneously. Constraint (4) determines the completion time of work in a bay, and Constraint (5) ensures that the workload in a bay—measured by the number of containers—matches the total work performed by a crane within the planning horizon. Constraint (6) specifies that once assigned, a crane remains in a bay until all work in that bay is completed. Constraint (7) defines the vessel's work as complete only when all its bays are finished, and Constraint (8) identifies the specific time when this occurs. Constraint (9) ensures that the vessel's work is completed within the planning horizon. Constraints (10) to (13) ensure vessels remain moored at the quay throughout their handling time, while Constraint (14) determines the available berthing space. Constraints (15) and (16) establish the sequence in which vessels are positioned along the quay, and Constraint (17) identifies the positions of individual bays on each vessel. Constraints (18) and (19) align crane positions with the corresponding bay positions. Constraints (20) and (21) govern the placement of cranes along the quay, while Constraint (22) ensures they maintain a safe operational distance from each other. Constraints (23) to (27) account for tidal conditions, restricting quay access for vessels with deep drafts during low tide. Finally, Constraints (28) and (29) define the types of decision variables used in the model. Given that the model is NP-Hard, Malekahmadi[10] presents a PSO-based meta-heuristic approach, known as the Random Topology Particle Swarm Optimization (RTPSO) algorithm, to solve it. Due to its NP-hard nature, finding an optimal solution through linear programming methods is not feasible. The Quay Crane Scheduling Problem stages can be outlined as follows:

Identifying quay cranes (QCs) available for operation at the dock.

Determining the most efficient loading and unloading sequence for each QC, ensuring that multiple optimization criteria are met.

The ship's stowage plan, prepared by the user or operator, dictates the location of containers to be unloaded and loaded[12], [13], [14]. This plan is based on container type and the ship's voyage route, aiming to balance the vessel to avoid affecting its speed or efficiency during operations. Consequently, the sequence of loading and unloading tasks for QC must meet certain conditions:

Unloading must precede loading operations.
Ship unloading must occur before unloading to the truck.
Loading onto the truck must occur before loading onto the ship.

The berth allocation problem is a key issue in port management, involving the assignment of berthing time and positions to incoming vessels [15]. As global maritime trade increases, optimizing berth allocation becomes even more essential for ensuring smooth port operations and reducing costs [16]. The complexity of the berth allocation arises from the numerous possible combinations for assigning ships to available berths [17]. In recent literature, various approaches have been explored to address the complexities of the berth allocation problem. Budipriyanto *et al.* [18] employed discrete event simulation to model berth planning, which allows for a dynamic analysis of port operations by simulating the arrival and departure of vessels, as well as the utilization of berths. Jos *et al.* [16], Prencipe and Marinell [17], Wawrzyniak *et al.* [19], Kramer *et al.* [20], and Martin *et al.*[21] developed mixed-integer linear programming model to optimize berth allocation with metaheuristic method. Prencipe *et al.* [17] focused specifically on the Discrete and Dynamic Berth Allocation Problem (DDBAP) by integrating Mixed Integer Linear Programming with Bee Colony Optimization. This combination aims to efficiently solve large-sized combinatorial berth allocation problems, demonstrating a significant advancement in optimization techniques applicable to real-world scenarios. Issam *et al.* [22], Bacalhau *et al.* [23], Nishi *et al.* [24], Yu *et al.* [25] and Barbosa *et al.* [26] solved dynamic berth allocation problems using modified metaheuristic methods, including the sailfish optimizer, particle swarm optimization algorithm, and dynamic programming-based metaheuristics.

Solving berth allocation problem poses significant challenges when employing mixed-integer linear programming and metaheuristic approaches, primarily due to the complexities involved in managing flexible vessel priorities and the inherent variations in cargo and material handling processes. Yildirim *et al.* [27] and Li *et al.* [28] have approached berth allocation problem through simulation optimization, a method that allows for dynamic decision-making in complex environments. Simulation optimization enables the modeling of various operational scenarios and the evaluation of different allocation strategies, thereby providing insights into optimal berth assignment under varying conditions. These studies highlight the effectiveness of simulation optimization in addressing the inherent uncertainties of port operations and improving overall berth utilization. By incorporating real-time data and operational constraints, their methodologies contribute to more efficient and responsive berth allocation solutions. Both studies underscore the growing importance of simulation and optimization techniques in improving berth allocation efficiency, enhancing service quality, and addressing the complexities associated with dynamic port operations. The integration of these methods provides a robust framework for optimizing berth utilization and minimizing vessel waiting times.

Algorithm Development

In one year, a total of 57 vessels were involved in unloading and 185 vessels in loading operations at a dry bulk port. The material handling operations are categorized into two groups: unloading material handling and loading material handling. For unloading, there are two units of CSU (CSU I and CSU II), two units of KC (KC I and KC II). Cargo is distributed from the dock to the warehouse using conveyors and trucks. In instances where the primary material handling equipment is unavailable, the unloading process will be carried out by auxiliary material handling equipment. For loading operations, there are two types of material handling, namely NSL and VC.

The port is divided into seven areas: Piers A, B, C, D, E, F, and G. Piers A, B, C, and D prioritize vessels with Length Overall (LOA) greater than 100 meters, while Piers E, F, and G are designated for vessels with LOA of less than 100 meters. Each type of material handling equipment varies in capacity and is assigned to specific piers, as outlined in Table 1. In the existing setup, each material handling unit operates within its designated area, as shown in Figure 1. This arrangement promotes flexibility in material handling and prevents overlap between different handling operations. In this study, two algorithms were developed to address the berth allocation problem, aimed at optimizing port operations. These include:
Dry Bulk Cargo Unloading Process Algorithm
Dry Bulk Cargo Loading Process Algorithm

Both algorithms were designed with the objective of minimizing demurrage costs by reducing the time required for loading and unloading operations. This was achieved through an optimal strategy for determining vessel berthing locations and assigning material handling resources efficiently.

Table 1. Material handling specifications

Material Handling	Loading/ Unloading Rate (Metric Tons/ Hour)	Pier
CSU I	401	D, G
CSU II	569	A, E, F
KC I	141	B
KC II	141	C
NSL	380	NSL Area

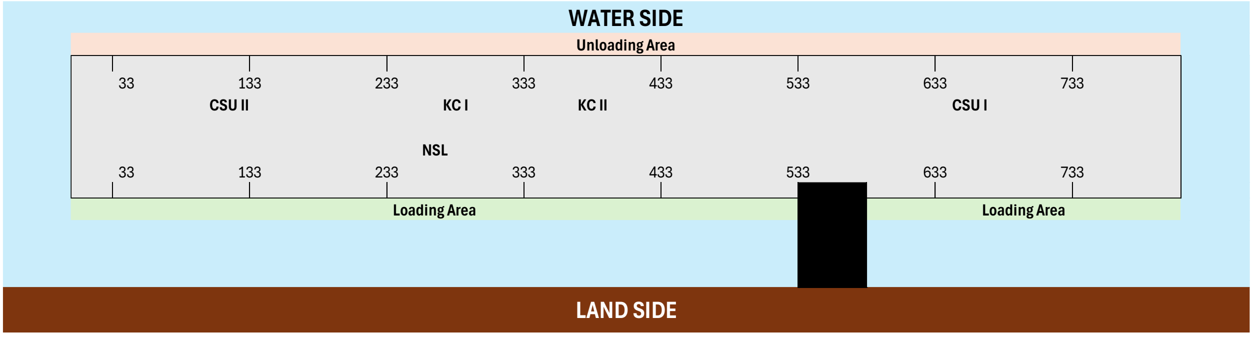

Figure 1. The layout of dry bulk terminal

The data originates from records of ship arrivals and cargo handling processes at bulk ports throughout 2023. To determine the appropriate distribution, a Chi-Square test was conducted with a significance level of 0.05, ensuring the best fit with a theoretical distribution. The results indicate that processing times for the same type of material handling follow a uniform distribution, as all handling units operate with identical capacity specifications. Consequently, cargo handling times are evenly distributed within a defined range, exhibiting no distinct patterns or significant variations, making the uniform distribution the most suitable representation. The data distribution for the loading and unloading processes used in the discrete event simulation is detailed in Tables 2 and 3.

Table 2. Data distribution for the loading process

Loading Process	Distribution
Time between arrival (hour)	-0.001 + 98 * BETA(0.731, 1.6)
LOA (m)	70 + 46 * BETA(1.18, 1.78)
Ship's cargo volume (100 tons)	10 + 91 * BETA(1.09, 1.24)
Loading processing time with NSL (hours)	NORM(45.8, 7.79)
Loading processing time with NSL-VCDT (hours)	31.5 + 25 * BETA(0.67, 0.703)

Table 3. Data distribution for the unloading process

Unloading Process	Distribution
Time between arrival (hour)	4 + 658 * BETA(0.633, 1.74)
LOA (m)	43 + 157 * BETA(2.31, 0.589)
Ship's cargo volume (100 tons)	106 + 4.39e+004 * BETA(1.37, 0.891)
Unloading processing time with CSU II (hours)	29.5 + 31 * BETA(0.914, 0.861)
Unloading processing time with CSU I (hours)	29.5 + 30 * BETA(0.846, 0.927)
Unloading processing time with KC I (hours)	34.5 + 18 * BETA(0.61, 0.772)
Unloading processing time with KC II (hours)	31.5 + 19 * BETA(0.371, 0.464)
Unloading processing time with External Equipment in CSU I & II (hours)	UNIF(5.5e+003, 4.67e+004)
Unloading processing time with External Equipment in KC I & II (hours)	UNIF(9e+003, 3.3e+004)
Unloading processing time with Conveyor of CSU II (hours)	28 + 4.34e+003 * BETA(0.268, 0.338)
Unloading processing time with Conveyor of CSU I (hours)	UNIF(77, 2.96e+003)
Unloading processing time with Conveyor of KC I & II (hours)	229 * BETA(0.494, 0.588)
Unloading processing time with dump truck KC (hours)	TRIA(44, 147, 158)

Berth Allocation Algorithm

The berth allocation simulation at the dry bulk terminal was designed using separate models for the loading and unloading processes. This approach reflects the specific conditions of the case study, where vessels dock to perform a single operation—either loading or unloading, but not both. Separation is crucial due to the different types of goods involved in these operations. As the terminal serves the internal logistics of a fertilizer company, it handles distinct materials for loading and unloading, each requiring specialized handling processes. This operational distinction demands a customized approach for each task to maximize efficiency and ensure effective resource allocation. By simulating these processes separately, the model can more accurately reflect the specific operational requirements and optimize berth utilization accordingly.

In the unloading process, CSU II is the primary equipment used for unloading on both the inner and outer sides of the dock. CSU II is prioritized because:

- It can access both sides of the dock.
- It offers the highest discharge rate compared to other equipment.
- It can deliver material to a greater number of warehouses.

An algorithm for berth allocation was developed to optimize the management of berth assignments and discharge processes at dry bulk terminals. The algorithm was divided into separate processes for unloading and loading operations, detailing how vessels are assigned to berths based on equipment availability, vessel characteristics, and operational readiness. The steps involved in the algorithm for unloading are as follows:

Step 1: Vessel Arrival Time
The algorithm starts by capturing the arrival time of the vessel at the port. This is the first step to initiate the process and will determine when the vessel enters the sequence for allocation.

Step 2: Check Availability of Piers
The system first checks if Piers A, B, C, E, F, or G are available. Each pier can accommodate vessels based on the vessel's Length Overall (LOA) and the availability of material handling equipment, as outlined in Table 1. A pier is considered available if its length matches the vessel's LOA and the material handling equipment is ready for use.

- For vessels with an LOA of 100 meters or less, the docking priority is as follows: Pier A is the first choice, followed by Pier D, then Pier B, and finally Pier C.
- For vessels with an LOA of less than 100 meters, the priority is Pier E first, then Pier F, and Pier G last. If these piers are unavailable, vessels can be accommodated at Piers A, D, B, or C, as long as no larger vessels are scheduled to dock.
- If the pier is available, the vessel proceeds to that pier.
- If no pier is available, the vessel waits in the harbor.

Step 3: Pre- Processing Handling for Unloading
Once the vessel is assigned to the appropriate pier, the algorithm initiates pre-time for processing activities to prepare the pier, material handling equipment, and storage facilities.

Step 4: Unloading Process
The unloading process utilizes the designated material handling equipment as specified in Step 1.
If the material handling equipment is unavailable due to a breakdown, the system uses external equipment to assist with the unloading process until the primary equipment is ready, ensuring smooth operations.

Step 5: Warehouse Readiness and Cargo Transportation
Once the material is unloaded, the algorithm checks the readiness of the warehouse to receive the cargo. CSU I and CSU II distribute cargo to warehouses directly connected to the conveyor system. KC I and KC II need to confirm whether the warehouse is connected to the conveyor.

- If the warehouse is connected to the conveyor, the cargo is transported using the conveyor system.
- If not, the cargo is transported using dump trucks to temporary storage until the warehouse is ready to receive the cargo. This applies specifically to cargo from vessels served by KC I and KC II.

Step 6: Post-Process and Ship Departure
After unloading, the vessel completes the post-unloading formalities.
The vessel then leaves the pier with the assistance of a pilot boat and a tugboat to safely depart from the port.

Step 7: Calculate berthing time, waiting time, dispatch and demurrage cost

$$BTU_i = WT_i + PrT_i + UT_i + PsT_i \tag{1}$$

Notation
I : number of ships served during the simulation period
BTU_i : the berthing time for unloading of vessel i $(i = 1,2,3, \ldots \mathrm{I})$
WT_i : the waiting time of vessel i before the vessel berth
PrT_i : the pre-process time of vessel i
UT_i : the unloading time of vessel i
PsT_i : the post-process time of vessel i

$$D_i = (TBT_i - BTU_i) \times DR_i \quad (2)$$

Notation
D_i : dispatch of vessel i
TBT_i : target of berthing time vessel i
DR_i : dispatch rate of vessel i

$$DC_i = (BTU_i - TBT_i) \times DcR_i \quad (3)$$

Notation
DC_i : demurrage cost of vessel i
DcR_i : demurrage cost rate of vessel i

The target berthing time is established through the contract between the port and the shipping company or shipper. It is set during the ship's berth booking process.

The type of material being loaded determines the equipment used in the loading process. Over 50% of the cargo loaded is bagged material. For bag cargo, the loading is carried out using a Vessel Crane Flat Truck (VCFT). For bulk material (non-bagged), the primary loading equipment is the New Ship Loader (NSL). NSL is preferred because it can service ships docked on both the inner and outer sides of the pier. Figure 3 represents an algorithm for managing berth allocation and the loading process at a dry bulk. This process ensures that ships are efficiently directed through the port by checking the availability of piers, equipment, and compatibility with the vessel's characteristics. Below is a detailed explanation of the algorithm for loading process:

Step 1: Vessel Arrival Time
The algorithm starts by capturing the arrival time of the vessel at the port. This is the first step to initiate the process and will determine when the vessel enters the sequence for allocation.

Step 2: Check the cargo and the availability of piers
If the vessel is loading cargo in bags, the system first checks whether loading pier is available. Each pier is capable of handling vessels based on the vessel's LOA.

If the pier is available, the vessel proceeds to that pier, and the loading process is carried out using VCFT. Flat trucks transport cargo from the warehouse to the pier, where the vessel crane loads the cargo onto the vessel.

If no pier is available, the vessel waits in the harbor.

If the vessel is loading bulk cargo, the system first checks the availability of the left-side loading area (NSL Area). Each pier can accommodate vessels based on their LOA.

If the NSL Area is available, the vessel proceeds to the designated pier, and the loading process is carried out using NSL and VCDT. Dump trucks transport cargo from the warehouse to the pier, where the NSL and the vessel crane loads the cargo onto the vessel.

If no NSL Area pier is available, the system checks the availability of the right-side loading area (Non-NSL Area). If Non-NSL Area pier is available, the vessel proceeds to that pier, and the loading process is performed using VCDT. Dump trucks transport cargo from the warehouse to the pier, where the vessel crane loads the cargo onto the vessel.

If no pier is available, the vessel must wait in the harbor.

Step 3: Pre-Process Handling for Loading/Unloading
Once a suitable pier is found, the algorithm initiates pre-processing time to prepare the pier, material handling equipment, and storage facilities for loading process.

Step 4: Loading Process
The loading process utilizes VCFT, NSL and VCDT or VCDT based on assignment in Step 2.

If the equipment is unavailable, the system turns into external equipment for assistance with the loading process, ensuring operations continue smoothly.

Step 5: Post-Process and Ship Departure
After loading, the vessel completes the post-unloading formalities.
The vessel then leaves the pier with the assistance of a pilot boat and a tugboat to safely depart from the port.

Step 6: Calculate berthing time, waiting time, dispatch and demurrage cost

$$BTL_i = WT_i + PrT_i + LT_i + PsT_i \quad (4)$$

Notation
I : number of ships served during the simulation period
BTL_i : the berthing time for loading of vessel i ($i = 1,2,3, \ldots$ I)
WT_i : the waiting time of vessel i before the vessel berth
PrT_i : the pre-process time of vessel i
LT_i : the unloading time of vessel i
PsT_i : the post-process time of vessel i

$$D_i = (TBT_i - BTL_i) \times DR_i \quad (5)$$

Notation
D_i : dispatch of vessel i
TBT_i : target of berthing time vessel i
DR_i : dispatch rate of vessel i

$$DC_i = (BTL_i - TBT_i) \times DcR_i \quad (6)$$

Notation
DC_i : demurrage cost of vessel i
DcR_i : demurrage cost rate of vessel i

Results and Discussions

Results

The simulation model was verified using the model check feature in the simulation software. The verification results indicated no errors, with the notification: "No errors or warnings in model". For validation, the simulation model was assessed using a t-test to compare the loading and unloading process times from the simulation results with the actual process times. The validation was conducted at a 95% confidence level, using the following hypotheses:

Unloading Process

$$H_0: \mu_1 = \mu_2$$

The unloading process in the simulation is equivalent to the actual unloading process.

$$H_1: \mu_1 \neq \mu_2$$

The unloading process in the simulation differs from the actual unloading process.

Loading Process

$$H_0: \mu_1 = \mu_2$$

The loading process in the simulation is equivalent to the actual unloading process.

$$H_1: \mu_1 \neq \mu_2$$

The loading process in the simulation differs from the actual unloading process.

First, we validated the number of ships generated in the simulation model against the actual data from the existing system. Based on the t-test results presented in Table 4, the t-stat value for the unloading time is −1.3527, while the t-critical two-tail value is 1.9845. Since the absolute value of t-stat is less than t-critical, the H_0 is accepted. This indicates that the unloading process in the simulation is statistically the same as the actual unloading process.

Table 4. T-Test results for the simulation of the unloading process

t-Test: Two-sample assuming equal variances		
	Variable 1	**Variable 2**
Mean	56.940	57
Variance	0.098	0
Observations	50	50
Pooled Variance	0.049	
Hypothesized Mean Difference	0	
Df	98	
t Stat	-1.352	
P(T<=t) one-tail	0.089	
t Critical one-tail	1.660	
P(T<=t) two-tail	0.179	
t Critical two-tail	1.984	

Table 5. T-Test results for the simulation of the loading process

t-Test: Two-sample assuming equal variances		
	Variable 1	**Variable 2**
Mean	184.96	185
Variance	0.039	0
Observations	50	50
Pooled Variance	0.0195	
Hypothesized Mean Difference	0	
df	98	
t Stat	-1.428	
P(T<=t) one-tail	0.0781	
t Critical one-tail	1.660	
P(T<=t) two-tail	0.156	
t Critical two-tail	1.984	

Based on the T-test results shown in Table 2, the t-stat value for the unloading time is −1.4289, and the t-critical two-tail value is 1.9845. Since the absolute value of t-stat is less than t-critical, the decision is to accept H_0. Additionally, we validated the berthing time for both loading and unloading processes by comparing the simulated results with actual port operations. The average berthing time for unloading was 6,795.52 hours, while loading, it was 1,576.52 hours. Since the t-stat is less than t-critical, H_0 is accepted. This implies that the unloading process in the simulation is statistically the same as the actual unloading process.

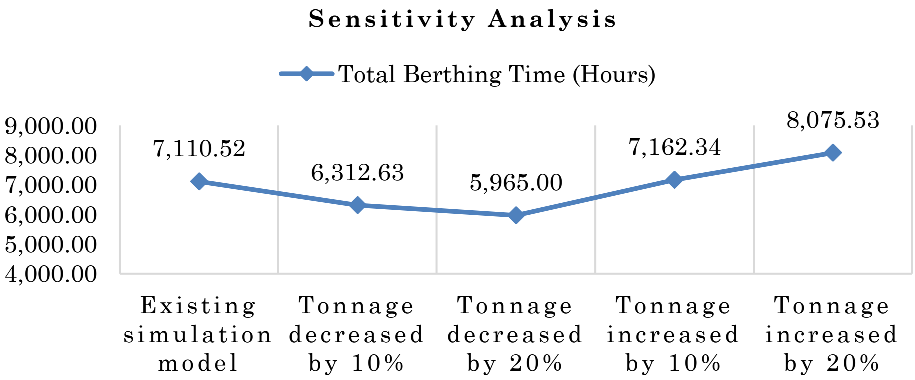

Figure 2. Sensitivity analysis

The sensitivity analysis of total berthing time highlights the system's responsiveness to variations in tonnage volumes. In the baseline scenario, the total berthing time is 7,110.52 hours to serve 57 vessels. When tonnage is reduced by 10%, the total berthing time decreases to 6,312.63 hours, reflecting an 11.22% improvement in operational efficiency. A further 20% reduction in tonnage results in a total berthing time of 5,965.00 hours, representing a 16.12% decrease compared to the baseline. Conversely, when tonnage increases, the system shows greater sensitivity. A 10% increase in tonnage leads to a slight rise in total berthing time to 7,162.34 hours, a 0.73% increase. However, a 20% increase results in a significant jump to 8,075.53 hours, corresponding to a 13.58% increase. This analysis underscores the system's efficiency in managing lower tonnage levels while revealing challenges in handling higher tonnage, particularly at a 20% increase, where delays become more pronounced. These findings emphasize the critical need for optimizing resource allocation and enhancing system capacity to ensure sustained efficiency under varying operational demands.

To determine the optimal unloading strategy, this research explored two potential improvement scenarios. The first scenario involved selecting the berthing location based on a vessel's Dead Weight Tonnage (DWT) and the availability of material handling equipment. The second scenario focused on berth allocation depending on the type of material to be loaded or unloaded, along with equipment availability. By comparing the current berth allocation algorithm with these two scenarios, the study assessed dispatch efficiency and demurrage costs to identify which strategy provides the most effective solution for port operations.

Scenario 1

In Scenario 1 for unloading, the berthing process was determined by the Dead Weight Tonnage (DWT) of each vessel. Ships with a DWT greater than 30,000 were berthed on the outer side of the pier and could be unloaded using CSU I, CSU II, KC I, KC II, or VCDT. Vessels with a DWT less than 30,000 were berthed on the inner side, where unloading can only be performed by CSU II and VCDT. The available equipment for unloading on the inner pier was limited by the equipment's operational reach. CSU II is prioritized for unloading due to its ability to service both the inner and outer sides of the pier, and its connection to a conveyor system that leads directly to the material warehouse, ensuring readiness and operational efficiency. The steps for Scenario 1 are outlined as follows:

Step 1: Vessel Arrival Time
The algorithm determines the sequence of vessels for berth based on the vessel arrival time.

Step 2: Check DWT
Before docking, the ship's DWT is checked. Ships with DWT greater than 30,000 are assigned to the outer side of the pier (unloading area) and proceed to Step 3a, while the DWT less than 30,000 are assigned to the inner side (loading area) and proceed to Step 3b.

Step 3a: Check Availability of Piers (Unloading Area)
The system first checks whether Pier A / E /F (CSU II area) is available. If so, it will be activated. If not, proceed to the next step.

If the CSU II area is unavailable whether Pier D/G (CSU I area) is available. If so, it will be activated. If not, proceed to the next step.

If the CSU I area is unavailable whether Pier B (KC I area) is available. If so, it will be activated. If not, proceed to the next step.

If the KC I area is unavailable, check whether the Pier C (KC II area) is available. If it is, it will be activated. If not, the ship will wait in the harbor.

Step 3b: Check Availability of Piers and Material Handling (Loading Area)
The system first checks whether NSL area is available. If so, it will be activated and checked whether the CSU II is available or not.

> If the CSU II is available, the vessel will be unloaded by CSU II.
> If the CSU II is unavailable, the vessel will be unloaded by VCDT.
> If the NSL area is not available, proceed to the next step.

If the NSL area is unavailable whether Non NSL area is available. If so, it will be activated, and the vessel will be unloaded by VCSDT. If not, the ship will wait in the harbor.

Step 4: Pre-Process Handling for Unloading
Once a suitable pier is found, the algorithm checks if the pre-process activities are done (e.g., preparing for the handling of materials, aligning the vessel correctly).

The vessel is then directed to the appropriate pier for loading or unloading, depending on the nature of the vessel's operation.

Step 5: Warehouse readiness and cargo transportation for KC units are managed similarly to the existing algorithm, ensuring efficient material flow and minimizing delays in operations.
Step 6: Unloading process and Ship Departure
Step 7: Calculate berthing time, waiting time, dispatch and demurrage cost

Scenario 2

The unloading process in Scenario 2 involved assigning berths and equipment based on the cargo type carried by each ship. The allocation of equipment and berthing locations was also adjusted to the conveyor lines and the availability of warehouse space for the specific cargo. The steps are as follows:

Step 1: Vessel Arrival Time

Step 2: Check the vessel's cargo
Before docking, the port reviews whether the vessel's cargo contains phosphate rock, sulfur, Muriate off Potash (MOP), or Ammonium Sulfate (ZA).
If the vessel's cargo is phosphate rock, proceed to the step 3a
If the vessel's cargo is sulfur or MOP, proceed to the step 3b
If the vessel's cargo is Za, proceed to the step 3c
If the vessel's is carrying other material, proceed to the step 3d

Step 3a: Check Availability of pier and CSU II
The system first checks whether Pier A / E /F and CSU II are available.
If Pier A / E /F and CSU II are available, the vessel berths to pier A/E/F and will be unloaded by CSU II.
If Pier A / E /F is available but the CSU II is not available, the vessel berth to pier A/E/F and will be unloaded by external equipment.
If not, the vessel will wait in the harbor.

Step 3b: Check Availability of Piers and CSU I
The system first checks whether Pier D/G and CSU I are available.
If Pier D/G and CSU I are available, the vessel berths to pier D/G and will be unloaded by CSU I.
If Pier D/G is available but the CSU I is not available, the vessel berth to pier D/G and will be unloaded by external equipment.
If not, the vessel will wait in the harbor.

Step 3c: Check Availability of Piers and KC I
The system first checks whether Pier B and KC I are available.
If Pier B and KC I are available, the vessel berths to pier B and will be unloaded by KC I.
If Pier B is available but the KC I is not available, the vessel berth to pier B and will be unloaded by external equipment.
If not, the vessel will wait in the harbor.

Step 3d: Check Availability of Piers and KC II
The system first checks whether Pier C and KC II are available.
If Pier C and KC II are available, the vessel berths to pier C and will be unloaded by KC II.
If Pier C is available but the KC II is not available, the vessel berth to pier B and will be unloaded by external equipment.
If not, the vessel will wait in the harbor.

Step 4: Pre-Process Handling for Unloading
Step 5: Warehouse readiness and cargo transportation for KC units
Step 6: Unloading process and Ship Departure
Step 7: Calculate berthing time, waiting time, dispatch and demurrage cost

The algorithm was also applied to the unloading process. The main distinction lies in how different material handling methods are allocated, as detailed below:
If the vessel's cargo is phonska bag, the vessel will be loading with VCFT

If the vessel's cargo is gypsum/ Neutralized Crude Gypsum (NCG)/ Diamonium Fosfat (DAP)/ Urea, the vessel will be loading with NSL
If the vessel's cargo is urea or Nitrogen Fosfat Sulfer (NFS), the vessel will be loading with NSL and VCDT
If the vessel's is carrying other material, the vessel will be loading with VCDT

Discussion

The results of this study are specific to the analyzed scenarios and cannot be generalized to all port operations. Therefore, the discussion focuses on determining which scenario is most effective under the given conditions, particularly considering specific vessel interarrival times and the availability of handling equipment. In the first scenario, berthing locations were assigned based on vessel Dead Weight Tonnage (DWT) and the availability of material handling equipment, ensuring that larger vessels with higher capacity requirements are allocated to suitable berths. However, this approach results in a slight increase in unloading time (6,860.13 hours) compared to the current system (6,795.52 hours), while reducing loading time to 1,460.66 hours (Figure 3). One possible reason for the increase in unloading time is that, while the berths are optimized for vessel size, the availability of handling equipment across different berths may not be fully utilized, leading to potential delays in certain cases. In contrast, the second scenario prioritizes berth allocation based on the type of material being handled while still considering equipment availability. This method proves to be more efficient, reducing both unloading time to 6,670.09 hours and loading time to 1,395.73 hours, making it the optimal choice for streamlining port operations. By aligning cargo type with specialized handling equipment, Scenario 2 ensures a more balanced utilization of available resources, preventing bottlenecks and improving overall efficiency.

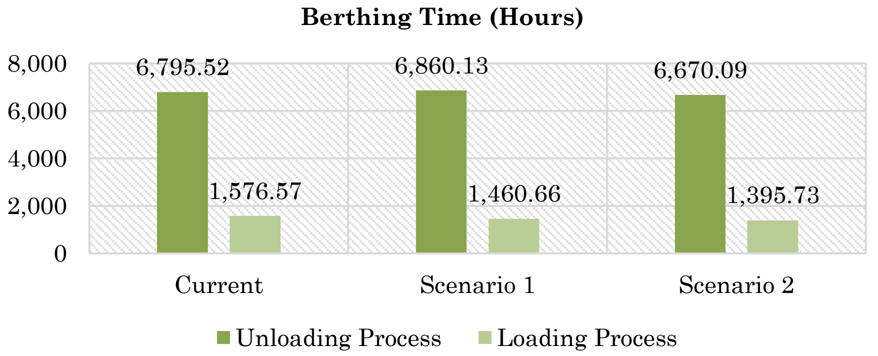

Figure 3. Berthing time (hours)

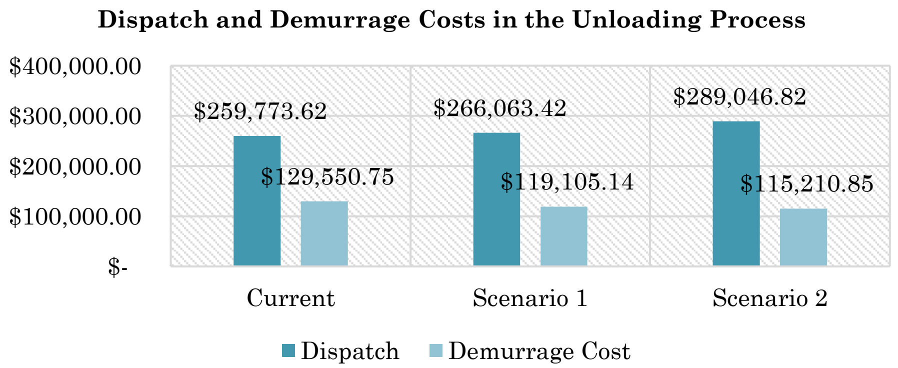

Figure 4. Dispatch and demurrage costs in the unloading process

With the minimum berthing time, Scenario 2 also produces the lowest demurrage costs and the highest dispatch costs compared to the current system and Scenario 1, as indicated in Figure 4. Figure 4 presents the dispatch and demurrage costs for the unloading process under three different scenarios. In the current system, dispatch costs are $259,773.62, with demurrage costs of $129,550.75. In Scenario 1, where berth allocation is based on DWT and equipment availability, dispatch costs slightly increased to $266,063.42, but demurrage costs decreased to $119,105.14. In Scenario 2, which focuses on berth allocation by material type and equipment availability, dispatch costs rose further to $289,046.82, while demurrage costs reduced to $115,210.85. This scenario demonstrates the lowest demurrage costs, suggesting improved efficiency in reducing vessel waiting times, although dispatch expenses are higher.

From Figure 5, which presents dispatch and demurrage costs in the loading process, Scenario 2 achieves the lowest demurrage cost at $29,972.79 compared to the current system and Scenario 1, which have costs of $38,371.51 and $32,938.19, respectively. Additionally, Scenario 2 also reflects a relatively high dispatch cost of $162,892.97, slightly lower than the current system but higher than Scenario 1. This analysis indicates that Scenario 2 significantly reduces demurrage costs, implying that delays and waiting times for vessels at the port are minimized. Furthermore, the higher dispatch cost suggests greater efficiency in the loading process.

For instance, when vessel interarrival times are tighter during peak delivery periods, the efficiency of Scenario 2 becomes even more evident. Since berth allocation is driven by material type, congestion is minimized, and the turnaround time is optimized. Additionally, by distributing handling tasks based on material rather than vessel size, the workload is spread more evenly across available equipment, increasing overall equipment utilization and reducing idle time. This suggests that Scenario 2 is more effective in high-traffic conditions, whereas Scenario 1 may be more suitable in cases where vessel size significantly impacts operational efficiency.

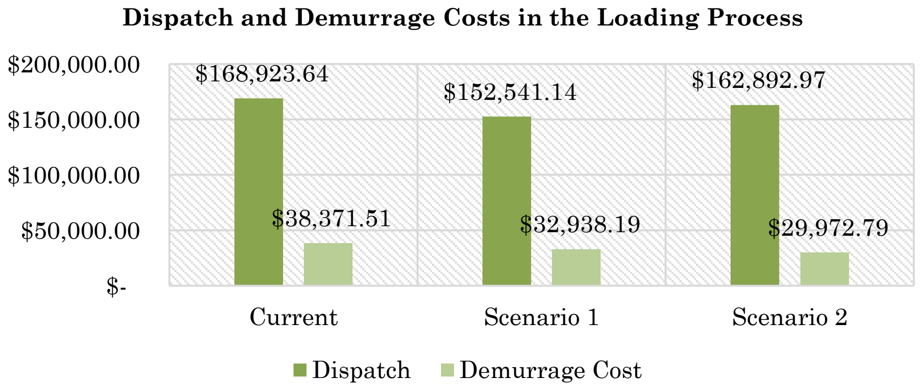

Figure 5. Dispatch and demurrage costs in the loading process

León et al. focus on disruption management for berth scheduling in bulk terminals, emphasizing the optimization of berth allocation during operational disruptions such as delays, vessel arrivals, and unforeseen circumstances[29]. Their approach uses adaptive strategies to manage real-time disruptions and minimize delays. Vianen et al. provide valuable insights into optimizing stockyard capacity for dry bulk terminals. While our research addresses a different yet complementary aspect of port operations by focusing on berth allocation policies. By integrating multiple criteria, including LOA, DWT, and cargo type, our study extends the application of discrete event simulation to reduce total berthing time by optimized berth allocation strategies while considering the availability of material handling resources.

The findings highlight the critical importance of efficient berth allocation in minimizing berth time, ultimately increasing revenue and improving overall port performance. Moreover, by reducing berthing time, demurrage is minimized, and dispatch is increased. A decrease in berthing time also leads to a reduction in the emissions produced by vessels, as well as lower consumption of material handling equipment that relies on both fossil fuels and electricity. By implementing the strategies from Scenario 2, shipping companies can optimize berthing time, allowing for more efficient deliveries. Additionally, the port can serve more vessels, increasing revenue for both the shipping company and the port authority, especially for the Dry Bulk Fertilizer Terminal. These operational optimizations also align with broader sustainability goals by improving environmental performance, reducing carbon emissions, and enhancing the economic viability of port operations while contributing to sustainable development in the shipping industry.

Conclusions

The existing loading and unloading simulation model employ a berthing strategy based on a plotting schedule established by Port Supervision and Service seven days in advance of the ship's arrival. The unloading process utilizes equipment such as CSU I, CSU II, KC I, KC II, and vessel cranes, with CSU II prioritized for its versatility in reaching all areas of the dock and numerous warehouses via conveyor systems. CSU II also boasts the highest discharging rate among the available equipment. For loading, equipment selection is determined by the type of cargo: bagged cargo is loaded using a vessel crane and flat truck, while bulk cargo is loaded with NSL due to its efficiency and reach. Simulation results indicated a demurrage cost of $129,550.75 and dispatch of $259,773.62 for the unloading process, alongside $38,371.51 in demurrage and $168,923.64 in dispatch for the loading process. Total waiting times recorded were 262.05 hours for unloading and 258.16 hours for loading. Following the development of the current simulation model, two proposed scenarios for improvement were introduced. Scenario 1 focuses on berth based on each vessel's DWT, while Scenario 2 centers on the specific cargo being loaded or unloaded. Based on the results, Scenario 2 is identified as the most effective approach to minimize demurrage costs and maximize dispatch revenue, yielding an increase of $43,613.10 in revenue for unloading and $2,368.05 for loading. This scenario is most effective under the given conditions, particularly considering specific vessel interarrival times and the availability of handling equipment. For future research, the stock level of warehouses needs to be considered. The raw material warehouse is directly linked to a conveyor system for loading cargo from incoming trucks. Unloading operations proceed efficiently when the warehouse stock levels are below the designated maximum capacity. However, when stock exceeds the maximum limit, a strategic approach is required to manage the unloading process. This ensures that unloading times are minimized and demurrage costs are kept under control, preventing delays and inefficiencies.

Acknowledgments

The authors wish to thank the reviewers for their valuable suggestions to improve the quality of this paper. We also express our gratitude to the Ministry of Education, Culture, Research, and Technology for their financial support of this research under the PDP scheme.

References

[1] V. EFECAN, "An application of the DEA-cross efficiency approach in Turkish dry-bulk and general cargo terminals," *Marine Science and Technology Bulletin*, vol. 12, no. 4, pp. 540–552, Dec. 2023, doi: 10.33714/masteb.1377896.

[2] S. H. Jeong, Y. S. Choi, M. Listan Bernal, and G. T. Yeo, "Analysis of obstacles to lowering demurrage at grain terminals in South Korea," *Asian Journal of Shipping and Logistics*, vol. 40, no. 1, 2024, doi: 10.1016/j.ajsl.2023.12.003.

[3] Y. Keceli, "A simulation model for gate operations in multi-purpose cargo terminals," *Maritime Policy and Management*, vol. 43, no. 8, 2016, doi: 10.1080/03088839.2016.1169448.

[4] A. D. de León, E. Lalla-Ruiz, B. Melián-Batista, and J. M. Moreno-Vega, "A simulation–optimization framework for enhancing robustness in bulk berth scheduling," *Engineering Applications of Artificial Intelligence*, vol. 103, 2021, doi: 10.1016/j.engappai.2021.104276.

[5] I. Castilla-Rodríguez, C. Expósito-Izquierdo, B. Melián-Batista, R. M. Aguilar, and J. M. Moreno-Vega, "Simulation-optimization for the management of the transshipment operations at maritime container terminals," *Expert Systems with Applications*, vol. 139, 2020, doi: 10.1016/j.eswa.2019.112852.

[6] I. Lovrić, D. Bartulović, M. Viduka, and S. Steiner, "Simulation analysis of seaport rijeka operations with established dry port," *Pomorstvo*, vol. 34, no. 1, 2020, doi: 10.31217/p.34.1.15.

[7] M. M. Putri, A. Rusdiansyah, and S. Nurminarsih, "Model of twin automatic stacking crane operation strategy with dynamic handshake area in an automated container terminal," *Jurnal Teknik Industri: Jurnal Keilmuan dan Aplikasi Teknik Industri*, vol. 25, no. 1, pp. 79–96, Jun. 2023, doi: 10.9744/jti.25.1.79-96.

[8] M. Neagoe, H. H. Hvolby, M. S. Taskhiri, and P. Turner, "Using discrete-event simulation to compare congestion management initiatives at a port terminal," *Simulation Modelling Practice and Theory*, vol. 112, 2021, doi: 10.1016/j.simpat.2021.102362.

[9] A. H. Gharehgozli, F. G. Vernooij, and N. Zaerpour, "A simulation study of the performance of twin automated stacking cranes at a seaport container terminal," *European Journal of Operational Research*, vol. 261, no. 1, 2017, doi: 10.1016/j.ejor.2017.01.037.

[10] A. Malekahmadi, M. Alinaghian, S. R. Hejazi, and M. A. Assl Saidipour, "Integrated continuous berth allocation and quay crane assignment and scheduling problem with time-dependent physical constraints in container terminals," *Computers & Industrial Engineering*, vol. 147, 2020, doi: 10.1016/j.cie.2020.106672.

[11] E. Lujan, E. Vergara, J. Rodriguez-Melquiades, M. Jiménez-Carrión, C. Sabino-Escobar, and F. Gutierrez, "A fuzzy optimization model for the berth allocation problem and quay crane allocation problem(BAP +

QCAP) with n quays," *Journal of Marine Science and Engineering*, vol. 9, no. 2, 2021, doi: 10.3390/jmse 9020152.

[12] X. Sun, S. Wang, Z. Wang, C. Liu, and Y. Yin, "A semi-automated approach to stowage planning for Ro-Ro ships," *Ocean Engineering*, vol. 247, 2022, doi: 10.1016/j.oceaneng.2022.110648.

[13] J. Li, Y. Zhang, S. Y. Ji, and J. Ma, "Inland container ship stowage planning decision with multiple container types," *Jiaotong Yunshu Xitong Gongcheng Yu Xinxi/Journal of Transportation Systems Engineering and Information Technology*, vol. 19, no. 1, 2019, doi: 10.16097/j.cnki.1009-6744.2019.01.030.

[14] Y. Wang, G. Shi, and K. Hirayama, "Many-objective container stowage optimization based on improved NSGA-III," *Journal of Marine Science and Engineering*, vol. 10, no. 4, 2022, doi: 10.3390/jmse10040517.

[15] S. C. Chang, M. H. Lin, and J. F. Tsai, "An optimization approach to berth allocation problems," *Mathematics*, vol. 12, no. 5, 2024, doi: 10.3390/math12050753.

[16] B. C. Jos, M. Harimanikandan, C. Rajendran, and H. Ziegler, "Minimum cost berth allocation problem in maritime logistics: new mixed integer programming models," *Sadhana - Academy Proceedings in Engineering Sciences*, vol. 44, no. 6, 2019, doi: 10.1007/s12046-019-1128-7.

[17] L. P. Prencipe and M. Marinelli, "A novel mathematical formulation for solving the dynamic and discrete berth allocation problem by using the bee colony optimisation algorithm," *Applied Intelligence*, vol. 51, no. 7, 2021, doi: 10.1007/s10489-020-02062-y.

[18] A. Budipriyanto, B. Wirjodirdjo, I. N. Pujawan, and S. Gurning, "A simulation study of collaborative approach to berth allocation problem under uncertainty," *Asian Journal of Shipping and Logistics*, vol. 33, no. 3, 2017, doi: 10.1016/j.ajsl.2017.09.003.

[19] J. Wawrzyniak, M. Drozdowski, and É. Sanlaville, "Selecting algorithms for large berth allocation problems," *European Journal of Operational Research*, vol. 283, no. 3, 2020, doi: 10.1016/j.ejor.2019.11. 055.

[20] A. Kramer, E. Lalla-Ruiz, M. Iori, and S. Voß, "Novel formulations and modeling enhancements for the dynamic berth allocation problem," *European Journal of Operational Research*, vol. 278, no. 1, 2019, doi: 10.1016/j.ejor.2019.03.036.

[21] B. Martin-Iradi, D. Pacino, and S. Ropke, "The multiport berth allocation problem with speed optimization: Exact methods and a cooperative game analysis," *Transportation Science*, vol. 56, no. 4, 2022, doi: 10.1287/trsc.2021.1112.

[22] E. H. Issam, A. Lajjam, M. El Merouani, and Y. Tabaa, "A modified sailfish optimizer to solve dynamic berth allocation problem in conventional container terminal," *International Journal of Industrial Engineering Computations*, vol. 10, no. 4, 2019, doi: 10.5267/j.ijiec.2019.4.002.

[23] E. T. Bacalhau, L. Casacio, and A. T. de Azevedo, "New hybrid genetic algorithms to solve dynamic berth allocation problem," *Expert Systems with Applications*, vol. 167, 2021, doi: 10.1016/j.eswa.2020.114198.

[24] T. Nishi, T. Okura, E. Lalla-Ruiz, and S. Voß, "A dynamic programming-based matheuristic for the dynamic berth allocation problem," *Annals of Operations Research*, vol. 286, no. 1–2, 2020, doi: 10.1007/s10479-017-2715-9.

[25] M. Yu, Y. Lv, Y. Wang, and X. Ji, "Enhanced ant colony algorithm for discrete dynamic berth allocation in a case container terminal," *Journal of Marine Science and Engineering*, vol. 11, no. 10, 2023, doi: 10.3390/jmse11101931.

[26] F. Barbosa, P. C. B. Rampazzo, A. T. de Azevedo, and A. Yamakami, "The impact of time windows constraints on metaheuristics implementation: A study for the discrete and dynamic berth allocation problem," *Applied Intelligence*, vol. 52, no. 2, 2022, doi: 10.1007/s10489-021-02420-4.

[27] M. S. Yıldırım, M. M. Aydın, and Ü. Gökkuş, "Simulation optimization of the berth allocation in a container terminal with flexible vessel priority management," *Maritime Policy and Management*, vol. 47, no. 6, 2020, doi: 10.1080/03088839.2020.1730994.

[28] X. Li, Y. Zhao, P. Cariou, and Z. Sun, "The impact of port congestion on shipping emissions in Chinese ports," *Transportation Research Part D: Transport and Environment*, vol. 128, 2024, doi: 10.1016/j.trd. 2024.104091.

[29] A. Dávila De León, E. Lalla-Ruiz, and B. Melián-Batista, "Disruption management approaches for berth scheduling in bulk terminals," *Journal of Advanced Transportation*, vol. 2022, 2022, doi: 10.1155/ 2022/8069796.