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Waterway, Anchorage, and Berth Scheduling: A Case Study on Port of Manila

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Abstract. Maritime transport is a huge instrumental engine of trade economy following the nation's GDP growth. Short turnaround times and reduced waiting times play an important role in increasing countries' port competitiveness. Port operators need to establish an efficient port schedule through the minimization of ships' completion times. In this regard, vessels need to undergo sequential phases – inbound passage in waterway, anchorage queuing, berth allocation, and outbound passage. Technical limitations must also be addressed such as traffic capacity, safety distance, and berth spatial constraints. In this paper, the dependency of these phases will be solved in an integrated manner through the reformulation of the classic MM-RCPSP. The novelty of multi-alternative waterways considering safety distance will be explored, and port capacity restrictions are imposed to effectively replicate the real-life port situation. Data set from Port of Manila is generated to verify and validate the feasibility of the established MILP model. Computational results show that the proposed approach is effective in minimizing the completion time of vessels with a decrease of about 16.51% from the actual port performance.

Keywords: port efficiency, port congestion, port scheduling, RCPSP, MILP

1. Introduction

The focal transportation mode of global trade moves on water as about 12.4 billion tons of goods is transported across the world's ports with a total annual shipping trade value of more than $14 trillion [1]. The performance of port terminals is important because such affects the country's trade competitiveness. The lead metric for 2019 port turnaround times is the average port call hours which is measured from the time the ship reaches the anchorage until it departs from the berth [2]. The average time a vessel spent in a port is 23.2 hours or 0.97 days [3]. In the Philippines, the average port call hour is 31.7 hours which falls beyond the set metric. Philippine Port Authority (PPA) General Manager Jay Daniel R. Santiago already warned that prices of imported goods may rise and people may experience delays as shipping rates continued to soar. Shipping rates are increasing due to port congestions as operational disruptions cause extended ship port call times [4].

Based on the voyage charter, each contracted vessel must visit a defined number of ports, the volume of cargo to be transported, in a defined length of time. Port operators, as the service providers, need to keep up with the vessel's schedule, thus, must minimize the vessel's turnaround time at port. At this point, vessels undergo four processes. First, the vessel needs to pass the waterway to reach the berth area. The country's territorial waters are often divided into several fairways to cater numerous and simultaneous incoming ships. Safety distance between ships and traffic capacity inside each waterway must be maintained by the port operators. As it reaches the port area, the vessel will be assigned to a berth based on its spatial capability to serve the vessel. However, if there is no available berth, vessels cannot queue up in the waterway to let new incoming ships pass through, thus, vessels must park at the anchorage to wait. Since berth is available and cargo is already loaded or unloaded, vessels depart and pass the same waterway. A two-way waterway is involved, thus, safety distance of vessels moving in opposite directions must also be maintained by the port operators.

Reference [5] developed a MILP model dedicated to minimizing the weighted completion times of all ships at the third stage. The authors use Hybrid Flowshop Scheduling Problem (HFSP) to simultaneously

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model waterway scheduling, berth allocation, and quay crane assignment. Further, the system involves three main stages such as entering the waterway, berth and quay crane assignment to ships and exiting the waterway. Minimum Safety Time Interval (MSTI) was introduced to ensure safety distance before entering the waterway to avoid collisions. On the second stage, ships are either waiting, equivalent to buffer, or assigned in a berth. Quay cranes are limited and shared among ships, and the length of service time is according to the number of quay cranes assigned. The environment is almost the same as the study of [6]. However, unlike the previous paper, the speed of the ships is not different, thus, there is an imposed speed limit that must be maintained. Both of the aforementioned papers only consider a single two-way waterway. Also, anchorage queueing is not included as a temporary area before berth allocation and unlimited waiting time at berth is considered.

The model of this paper, which is the work of [7], extends MM-RCPSP to minimize total completion times in the waterway stage. Analyzation of the effect of multiple waterways is explored, and waterways are not only resource-dependent but also time-dependent. However, safety distance, anchorage queueing, and berth allocation are not considered. Alike the work of [7], [8] also minimizes the total transit time using MILP. The waterway that is considered is the Kiel Canal which is an artificial single waterway. Such has segments with different lengths and widths and sidings that are used by ships to wait until segments are available. Further, safety distances between ships are secured.

Based on the limitations of the present literature related to the port's operational efficiency, there is a need to develop a mathematical optimization model that minimizes total completion times of all ships under the schedule window by considering the dependency of passage time on a multi-mode waterway, waiting time in anchorage, and berth servicing time, while exploring the constraints of traffic capacity in multi-waterway and berth spatial limitation. This research aims to solve waterway scheduling and anchorage-berth scheduling in an integrated manner to avoid sub-optimal solutions in minimizing the completion time of all ships. The main contributions of this paper are as follows: (1) Scheduling of multi-mode waterway with the consideration of safety distance and traffic capacity, (2) Consideration of spatial constraints of determining berth eligibility vis-à-vis vessels' various dimensions, and (3) Novelty of including the waiting time at anchorage as part of the optimization model to ease congestion and serves as temporary area while waiting for an eligible berth.

2. Literature Review

One of the most important concerns in port connectivity refers to the availability of accessible waterways and traffic management. Due to this, inefficient use of the limited capacity of waterways may result in loss of port competitiveness and will add to the delay. Only few works focus their attention on waterway scheduling. Some analogies exploited the similarities maritime movements with the problem of scheduling trains on single track networks through Mixed Integer Linear Program (MILP)-based heuristic [9]. They provided experimental analysis on instances representing the ship movements in the Port of Venice. Reference [10] introduce three different types of waterways in China – one-way waterways, two-way waterways, and compound waterways by modelling a vessel-scheduling optimization using Multi-Objective Algorithm (MOGA) and compared such to first-come-first-serve (FCFS). However, only one waterway is modelled and resolved. Aside from natural waterways, the Kiel Canal, an artificial waterway of about 100km that connects the North Sea and the Baltic Sea was the paper setting of [8]. It can be concluded that the proposed approaches in the literature are restricted to the specifications of the studied waterways. Reference [11] introduced Waterway Ship Scheduling Problem (WSSP) a general approach for addressing the scheduling of traffic along the waterways. and proposes a model which considers the width, depth, and capacity of the waterway along with the draft limit of ships. The problem is modeled as MILP and addressed the situation in Yangtze Estuary, Shanghai. The modeling approach is motivated by vehicle routing problems. Reference [7] propose and reformulates WSSP as a Multi-Mode Resource-Constrained Project Scheduling Problem, which turns out to be superior to the work of [11]. The scheduling problem involves different waterways, that serve as multi-mode, with time-dependent resource capacities and task start time windows. The work of [7] suggests the application of MM-RCPSP to related maritime scheduling problems could produce promising research lines.

An ideal situation is in which all berths are available all the time and any ship can occupy the berth. This situation is impossible to achieve in practice because of the random arrival of ships and there are variations of ship sizes. In the berthing process, ships arriving at the terminal must wait until an available berth is free, and such is a proper slot for the ships' needs. Anchorage planning problem was introduced by [12] wherein they determine optimal berth locations of incoming vessels in the anchorage area with the goals of minimizing utilization of anchorage while minimizing the risk of accidents by ensuring safety distance between vessels in the anchorage. Reference [13] aims to develop a mathematical model of simultaneously optimizing navigation channel and anchorage utilization, wherein anchorage serves as a buffer when the navigational channel runs out of capacity. They minimize the total penalty of berthing tardiness and cost of unsatisfied service requests of vessels. Reference [14] minimize the berthing and departure delays and the number of vessels that cannot berth or depart successfully due to congestion in the navigation channel and anchorage areas in the terminal basin. Reference [15] integrates the vessel traffic for traveling into and out of the seaport with set tidal windows and allowing them to wait at anchorage. They incorporated the vessel traffic optimization and utilization of anchorage areas with decision of pilot scheduling for congestion minimization.

As the central point at the port, berth scheduling is deeply studied over the past two decades. The berth scheduling problem (BAP) aims to optimally assign berth positions and berthing times. There are limiting factors that are considered in the literature that affects berth eligibility such as quay crane availability, tidal constraints, and spatial constraints. Reference [16] introduce the BAP model under time-dependent limitations to a two-period planning horizon (low tide period and high tide period). The available water depth at low tide may not be adequate for handling some vessels since it can give rise to accidents at the port. However, when the departure time of the vessel exceeds the allowable period, the previous model is already infeasible. Such problem is addressed by [17] by proposing a model that schedules available berthing positions for the vessels arriving in the port terminal either low-tide or high-tide to infinity. Such allows scheduling of vessels that are berthed during the second period (high tide) and ends during the first period (low tide) and vice versa. In their model, vessels are assigned to berths regardless of the situation of the tide. These papers aim to minimize the servicing time of vessels at berth and the system is assumed to start in the arrival time of vessels at port. Another limiting factor is the spatial constraint of berths. Port quay is divided into finite independent berths with fixed length and each berth is capable of handling one vessel at a time. Further, berths may have different dimensions, and vessels' Length Overall (LOA) must be within the length of berth to safely maneuver vessels during the berthing and un-berthing process. Based on the design of vessel sizes of usual ship calls in a port, the minimum length of berths is considered for the port layout development [18]. References [19], [20], and [21] consider spatial constraints in which vessels are allowed to be serviced at any berth with acceptable physical conditions (i.e. berth length). The mentioned authors aim to minimize the service time at berth of all incoming vessels at port.

3. Methodology

3.1. Problem Definition

The system being considered in this paper is composed of four major stages: (1) incoming passage in the waterway, (2) anchorage queueing, (3) berth assignment, and (4) outgoing passage in the waterway (Figure 1). The objective is to establish an optimal schedule throughout these stages wherein visiting vessels will have minimum completion time.

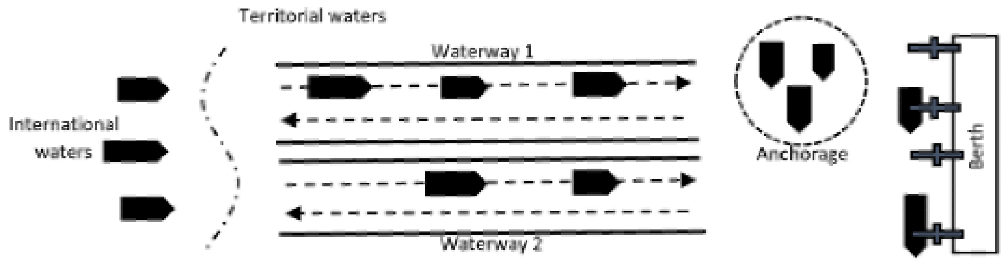

Fig. 1: Main processes in Maritime Operations

MM-RCPSP, a well-known model to solve scheduling problems, is reformulated to fit maritime settings. Task/job in MM-RCPSP will be introduced as vessel $j \varepsilon J$ that arrives and departs the port terminal. Before entering the territorial waters from international waters, Estimated Start Time (EST) is already assigned to each visiting vessel as communicated by ship operators to port operators. A waterway (mode) is assigned by port operators to each vessel (task) $j \varepsilon J$ and each waterway (mode) could be used by the incoming or outgoing vessel. Mode assignment depends on the traffic capacity inside each waterway. The traffic capacity metric is measured by the number of vessels that are allowed to pass through the waterway with respect to safety distance. Since each waterway has a defined traffic capacity and safety distance must be ensured, the waterway is the first resource constraint in this paper. Furthermore, the mode durations are equivalent to the waterway travel times of the ships (i.e. waterway 1 can have larger capacity but with longer travel duration than waterway 2). Once vessels entered the territorial waters, speed adjustment is required until the speed limit is achieved as instructed by port operators. Thus, there is a constant speed and constant distance between ships that must be maintained throughout the waterway to avoid accidents.

Once the inbound passage is done, which is denoted by arrival time at port, ships are either waiting in the anchorage or permitted to berth. The next stage of the system is the anchorage queueing wherein First In First Out (FIFO) policy is followed. Anchorage has a maximum number of waiting vessels to avoid overloading and port quay is divided into a defined number of berths. If a berth area is open for loading or unloading of cargos, such must be eligible first before berthing from the anchorage. Each berth has an assigned length, and the Length Overall (LOA) of the ship must be less than or equal to the berth length. Lastly, once loading or unloading is already done (third stage), the ship will do the outbound passage or the fourth stage, denoted by departure time.

3.2. Mathematical Model

In this section, the formulated model to solve the aforementioned problem through mixed-integer linear program is presented. The classic project scheduling problem shall be reformulated to fit the port operations requirements. Furthermore, resource constraints are incorporated into the traffic capacity inside the waterway, anchorage queueing, and berths' capacity to handle vessels. Also, the following assumptions are considered for the model:

- Information on the arrival of all ship calls included in the planning horizon, waterway specifications, and ship dimensions are known in advance. As a deterministic scenario is considered, parameters are known priori.
- The total width consumption by the ships entering and exiting the waterway must not exceed the waterway width including the safety distance between ships. Meaning there is a fixed division on the waterway for the incoming and outgoing ships.
- Speed and distance between ships will remain constant throughout the passage time. This is to correspond with the assigned speed limit in practice.
- The capacity of the system (waterway, anchorage, berth) is considered to be finite.
- Each berth can only serve only one vessel during the service time. Length overall (LOA) of the ship must be within the berth length to be eligible. Water depth restrictions are not considered.
- The handling time of each berth is fixed and independent.

Table 1: Model Indices

Indices	
j_{in}	Incoming vessel
j_{out}	Outgoing vessel
m	Waterway (mode)
a	Anchorage
b	Berth
t	Amount of time

Table 2: Model Decision Variables

Binary Variables	
x_{mj}	1 if incoming or outgoing vessel is assigned in waterway m; 0
x_{jb}	1 if vessel is allocated in berth b; 0

Table 3: Model Parameters

Parameters	
EST_j	Earliest Starting Time of vessel j
LST_j	Latest Starting Time of vessel j
VL_j	Length of vessel j
BL_j	Length of berth b
j_{ta}	Number of vessels interval that must meet t_{ja}
t_{ja}	Amount of time needed to meet by vessels separated by j_{ta}
M	Largest number
t_{mjin}	Incoming duration of vessel j under waterway m
t_j	Completion time of vessel j
λ_j	Arrival time of vessel j at anchorage
μ_j	Service time of vessel j in berth b
t_{jb}	Start if berth b is not occupied
t_{mjout}	Outgoing duration of vessel j under waterway m

The mathematical model from the analyzed relationship between parameters is as follows:

$$\min \Sigma(t_j - EST_j) \quad (1)$$

$$EST_j \leq \Sigma m\ (t_{mjin}) \leq LST_j;\ \text{for } \forall j \quad (2)$$

$$t_{mjin} \leq x_{mjin}\ (M);\ \text{for } \forall m,j \quad (3)$$

$$\Sigma m\ (x_{mjin}) = 1;\ 0;\ \text{for } \forall j \quad (4)$$

The stated objective function (1) is the reformulation of project makespan minimization, the typical objective of MM-RCPSP, wherein tasks in a project is scheduled optimally. The objective of this paper is to minimize vessels' (task) completion times wherein the sum of vessels' (task) start times is subtracted. Constraint (2) enforces the start time of each vessel in either of the mode (waterway) is not before its earliest start time and not after its latest start time. Equation (3) ensures that only 1 incoming vessel can take a value to avoid double counting and equation (4) assure that the incoming vessel is scheduled and exactly 1 mode is chosen.

$$\lambda j \geq \Sigma m\ (t_{mjin}) + \Sigma j\ \Sigma m\ (x_{mjin}\ t_{mjin});\ \text{for } \forall j \quad (5)$$

$$\lambda j + j_{ta} \geq \lambda j + t_{ja};\ \text{for } \forall m \quad (6)$$

$$\Sigma b\ (x_{jb}) = 1;0;\ \text{for } \forall j,b \quad (7)$$

$$BL_j \geq VL_{jb}\ (x_{jb});\ \text{for } \forall j,b \quad (8)$$

$$t_{jb} \geq \lambda_j;\ \text{for } \forall j \quad (9)$$

$$t_{jb} \geq x_{jb}\ (\mu_b);\ \text{for } \forall j \quad (10)$$

$$\mu_b \geq x_{jb}\,(t_{jb} + \mu_b);\ \text{for } \forall j,b \qquad (11)$$

$$\Sigma m(t_{mjout}) \geq \Sigma b\,(\mu_b);\ \text{for } \forall j \qquad (12)$$

Equation (5) is the arrival time at the port area or the time the vessel reaches the anchorage, while equation (6) is the number of vessels that can be accommodated by the anchorage with respect to the relaxing period. A relaxing period is injected to avoid overloading at the anchorage area. Afterward, each vessel is scheduled and allocated in 1 berth for servicing (7). To ensure that the eligible berth is chosen, equation (8) shows that the vessel's length must be within the berth length. Equation (9) enforces that the start time at berth must be greater than its arrival time and must be greater than the occupied time of selected berth (10). Service time or the period the berth is occupied is stated in equation (11). Identical service time is assigned for all vessels. Equation (12) assure that a vessel can only leave after service time at berth.

$$t_{mjout} \leq x_{mjout}\,(M);\ \text{for } \forall m,j \qquad (13)$$

$$\Sigma\, x_{mjout} = 1;\ 0;\ \text{for } \forall j \qquad (13)$$

$$t_j \geq \mu_b + \Sigma j\ \Sigma m\,(x_{mjout}\ t_{mjout});\ \text{for } \forall j \qquad (15)$$

After service time at berth, equation (13) ensures that only 1 departing vessel can take a value to avoid double counting, and equation (14) assure that the outgoing vessel is scheduled and exactly 1 mode is chosen. Lastly, the time for the vessel to completely leave the system is stated in equation (15).

3.3. Data Collection

The model is translated into programming language through CPLEX 33.2.0 for feasibility validation. Input parameters are based on the generated ship calls from the Port of Manila. The data set contain 20 visiting ships, while the North Channel and South Channel of the mentioned port is the multi-alternative waterway. The waterway dimensions and travel periods are presented in Table 4.

Table 4: Waterway Data in Port of Manila

Waterway (mode)	Length (m)	Width (m)	Hypothetical Travel Duration (min)
South Channel	4,850	1,852	30
North Channel	2,222	1,000	15

4. Results and Discussion

This paper aims to schedule traffic of ships along the waterway, and queueing system between anchorage and berth while considering the spatial capacity of port quays. To solve the stated problem, MM-RCPSP is reformulated and MILP mathematical model is developed. For the assessment of the feasibility of the established model, real input parameters from the Port of Manila were gathered.

This section reports the computational results of the tested instances. The data set of input parameters, and the assigned mode (waterway) and berth according to the model outcome are shown in Table 5. Vessels 2, 4, 6, 7, 9, 10, 12, 13, 15, 16, 18, 19, and 20 are assigned to waterway 1, while the rest are assigned to waterway 2. Waterway 1 has larger traffic capacity than waterway 2, but the former has longer travel duration going to the arrival area at the port. Furthermore, spatial constraint in the model enforces berth eligibility according to the length of vessels and berth. After service time at berth, Vessels 3, 6, 9, 10, 13, and 16 are assigned to waterway 1 for outgoing passage.

The size of the formulation with respect to model variables and constraints is an indicator of model strength when solved via MILP. The model formulation in this paper involves 381 variables and 906 constraints (20 vessels-4 stages) while [7] have 1,800 variables and 390 constraints (30 vessel-2 stages). This shows that the optimality of the resulting solution requires smaller amount of computational effort which outperforms the model paper.

Table 5: Model Outcome

Model Output			
Vessel	***Mode Incoming***	***Allocated Berth***	***Mode Outgoing***
1	2	1	2
2	1	4	2
3	2	2	1
4	1	1	2
5	2	4	2
6	1	2	1
7	1	1	2
8	2	1	2
9	1	1	1
10	1	1	1
11	2	3	2
12	1	1	2
13	1	4	1
14	2	4	2
15	1	2	2
16	1	4	1
17	2	2	2
18	1	1	2
19	1	1	2
20	1	1	2

As this paper aims to be used as a suitable and practical tool by terminal operators, model outcome vis-à-vis the actual experience of each vessel were compared. Based on the line graph in Figure 2, a bottleneck occurred after serving vessel 16 in actual port performance, creating a surge in longer completion time, while, the model output shows no evidence of congestion inside the port area. Furthermore, the performance of 20 vessels under schedule demonstrates that the developed model minimizes the total completion of ships by about 16.51% or a slack period of 5400 minutes which is adequate to handle an additional five (5) more incoming vessels. This empirical evidence shows that the sooner vessels completed their tasks at the port, the port can handle more incoming vessels, thus, increasing the port's capacity to serve ships. Also, this performance metric can be translated to increase in port's competitiveness.

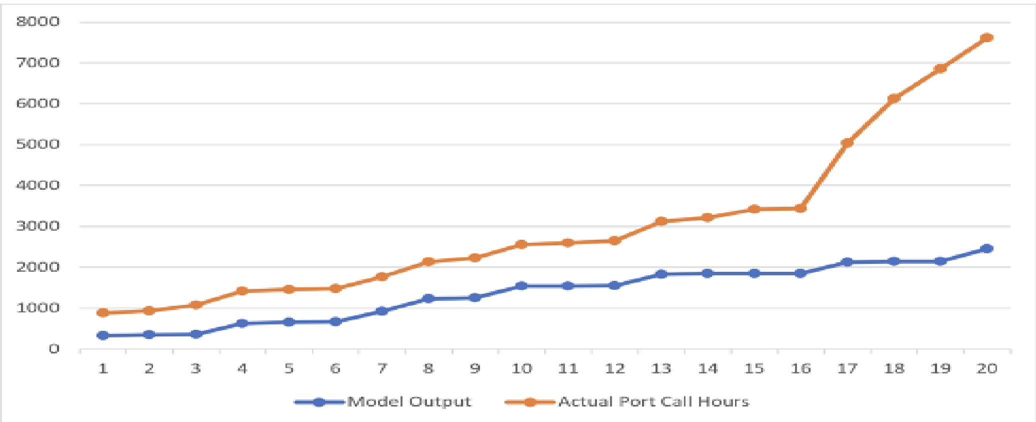

Fig. 2: Comparison between Model Output and Actual Port Call Hours.

The relative optimality gap computed by CPLEX and the running time (in seconds) are given in columns *gap %* and *CPU time*, respectively are presented in Table 6. The gap is calculated with respect to the optimal solution values by the model, which is presented under column *Objective Function*. By using the formulation in this paper, the optimal solution was able to obtain within 0.718 seconds for all the instances. Lastly, the optimal solution found is 22,525 minutes wherein each vessel has an average of 18.8 hours completion time, which is lower than the international metric of 23.2 hours, and average port call hours of 33.7 hours in the Philippines in 2021.

Table 6: Solutions Obtained from the Formulated Model

Objective Funtion (mins)	CPU time (sec)	Gap %
51478.0866	0.03	75.31
23391.5403	0.02	54.81
25692.5866	0.03	52.34
28414.1871	0.03	51.29
25072.6204	0.03	11.76
26606.0334	0.03	5.76
26540.3594	0.03	5.53
23314.6288	0.02	0.33
25127.9253	0.03	0.22
22525.0000	**0.00**	**0.00**

The results show that the classic RCPSP is applicable in solving port scheduling problems covering waterway traffic management, anchorage queueing, and berth allocation. Such is evident as port operations' structure is much alike with projects. Ports also have limitations when it comes to resources (i.e. traffic capacity, anchorage capacity, port quay capacity), and activities (vessels) can be performed (traversing times) in different modes (waterways).

From an operational and managerial point of view, this optimization model effectively replicates practical situations as vessels arriving at territorial waters undergo sequential processes. Scheduling vessels by port operators are bounded by technical issues including the safety of vessels inside the waterway, the dimensions of vessels visiting the port, and the spatial capability of berths to serve the vessels. Minimization of completion time of vessels through optimal schedule is translated to higher capacity to sustain increasing demand of visiting vessels, and higher revenue. Lastly, shorter turnaround times reflect satisfied ship operators, thus, in turn, contributing to port's competitiveness. This metric is important to developing countries with limited resources but needs to serve the magnitude of incoming vessels as these countries are main sources of raw materials and serve as the world's factories.

5. Conclusion and Recommendations

This paper extends the works of [7] wherein they schedule incoming and outgoing vessels in multi-alternative two-way waterways through reformulation of MM-RCPSP. Limitations of the said paper and port bottlenecks as major causes of shipment delay in real-world seaborne trade were taken into account.

Port operators must schedule each vessel in a minimum completion time to increase port's competitiveness and revenue. In this regard, incoming and outgoing vessels are required to undergo the key processes inside the port – waterway passage, anchorage queueing, and berth allocation. Vessels are assigned to any of the waterways according to traffic capacity inside the fairway. After reaching the port area, vessels cannot queue up inside the waterway to let new incoming vessels, thus, vessels must wait in the anchorage. As the anchorage area has limited capacity, port operators must minimize overloading of vessels. Accordingly, the number of berths is also limited according to the quay length capacity. Once an eligible berth is available, berthing elapses, and service time at berth starts. Afterward, vessels depart from the port and pass the waterway again.

MM-RCPSP is reformulated according to maritime requirements and to resolve the scheduling problem at the port. The validity of the model was tested through CPLEX programming software. Real problem instances are considered through the utilization of ship call data in Port of Manila in a 24-hour schedule makespan. The results show an optimal outcome of an average of 18.8 hours completion time of each vessel which is within the international metric of 23.2 hours of United Nations Conference on Trade and Development (UNCTAD) in 2020, and average completion times at Port of Manila which is 33.7 hours in 2021. Furthermore, the MILP model in this paper provides an optimal solution using a smaller amount of computational effort for all the instances concerning the existing models.

All of the input parameters in this paper are deterministic, however, some parameters at port are stochastic which can be explored by future researchers. Furthermore, the limitation of anchorage capacity in relation to safety distance between ships to avoid accidents can be a significant consideration in future studies. Lastly, environmental issues such as minimization of hazardous gas emissions in the anchorage while waiting is a growing concern of some port operators.

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