Muli-Quay Combined Berth and Quay Crane Allocation Using the Cuckoo Search Algorithm

Sheraz Aslam[a], Michalis P. Michaelides[b] and Herodotos Herodotou[c]
Department of Electrical Engineering, Computer Engineering and Informatics, Cyprus University of Technology, Cyprus

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Abstract: This study investigates the combined berth allocation problem (BAP) and quay crane allocation problem (QCAP) while considering a multi-quay setting. First, a mixed integer linear programming mathematical model is developed based on various constraints and real port settings. Then, the multi-quay combined BAP and QCAP is solved using both the exact method and a metaheuristic optimization method, namely, the cuckoo search algorithm (CSA). This analysis pertains to a one-week planning scenario, utilizing data from a real port. The results of the comparative analysis show that the proposed CSA can provide a near-optimal solution ($<$1.02% from the optimal) at a fraction of the computational time (10 times faster), as compared to the exact solution. This makes it suitable for solving larger instances of the combined BAP and QCAP for bigger terminals and extended planning horizons.

1 INTRODUCTION

International maritime trade plays a pivotal role in the global economy, accounting for over 80% of the transportation of goods around the globe. Seaports play a crucial role in managing this substantial volume of goods, encountering various operational challenges such as berth allocation (BAP), truck scheduling, storage allocation, quay crane allocation (QCAP), and optimization of straddle carriers. To satisfy the increasing demand, it is essential for terminals to enhance their operations through the utilization of contemporary technologies and optimization-driven methodologies. Given this imperative requirement, there has been significant interest from both academia and industry in devising innovative and effective approaches to optimize terminal operations (Lind et al., 2020). At the terminals, berths and quay cranes (QCs) are considered two of the basic resources, and their efficient use can help to reduce the total turnaround time of vessels (Li et al., 2020). Hence, BAP and QCAP have been the most concerned optimization problems in port planning and operations (Aslam et al., 2020; Zheng et al., 2019).

[a] https://orcid.org/0000-0003-4305-0908
[b] https://orcid.org/0000-0002-0549-704X
[c] https://orcid.org/0000-0002-8717-1691

The primary operations of marine ports are categorized into three main areas: marshaling yard, seaside, and landside. The first involves loading and unloading containers from incoming vessels using quay cranes and other terminal resources. Inbound containers are stored in the marshaling yard. Finally, landside operations include activities related to dispatching containers to their final destinations using trucks or trains (Aslam et al., 2022a). Berths and quay cranes (QCs) are bottleneck resources in ports due to the limited coastal environment and complexity of port activities (Li et al., 2020). Single or multiple berth lines are used to berth arriving vessels, and QCs are used to perform loading and unloading operations. All vessels arriving at the port may wait at the anchorage, then enter the port and moor at their assigned berth section to perform loading and discharging operations. Since available berths and QCs are limited, good planning and proper coordination between them can improve terminal productivity. The BAP identifies berthing positions and berthing times for arriving vessels based on a variety of factors, such as expected time of arrival (ETA), handling time or total load, requested time of departure (RTD), etc. In addition, the QCAP deals with the appropriate allocation of cranes based on the BAP solution and availability of cranes, since BAP and QCAP are interdependent problems (Yu et al., 2019).

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In the current literature, there are many studies dealing with stand-alone BAP (Aslam et al., 2022a, 2021; Bierwirth and Meisel, 2015; Theofanis et al., 2007; Ernst et al., 2017; Golias et al., 2009a,b; Alsoufi et al., 2016). For instance, the authors of Theofanis et al. (2007) solve a BAP with the objective of reducing the number of late departures at the port of Shahid Rajaee Shallow, Iran. Another study (Ernst et al., 2017) also addresses the BAP to optimize the departure times of vessels. The authors of Golias et al. (2009a,b) also address BAP with the goal of optimal berth allocation and propose heuristic-based solutions to solve the problem. The work presented in Alsoufi et al. (2016) also solves the BAP intending to reduce the late departure of vessels by efficiently allocating berths using a hybrid of genetic algorithm (GA) and branch-and-cut (B&C) methods. Currently, there is a growing tendency to address both BAP and QCAP concurrently, since the number of cranes (and which cranes in case of different handling productivity) assigned to a ship determines the berthing time of the vessels (Xiang and Liu, 2021; Rodrigues and Agra, 2022). Most of the current studies consider only a single quay, while they look at stand-alone BAP or combined BAP-QCAP (Rodrigues and Agra, 2022).

There are only a few studies dealing with terminals with multiple quays. For example, in a study presented in Frojan et al. (2015), a solution for multiple quays is proposed for BAP; however, in this study, the total length of the quay is divided equally between two quays and random data are used for the experiments. In addition, practical constraints are not considered. A recent study in Krimi et al. (2020), also solves the multi-quay BAP and concludes that the proposed method does not always provide an optimal solution and is sometimes 40% away from the optimal solution. In another work, Gutierrez et al. (2019) propose a fuzzy-based solution, but as the authors acknowledge, the proposed method provides an optimal solution when only up to 10 vessels are considered. In our own previous work, we have explored using metaheuristics, and in particular the cuckoo search algorithm, for addressing the multi-quay scenario with more practical settings but only for the standalone BAP Aslam et al. (2022b, 2023). We have found only a single research paper that addresses the combined BAP and QCAP while considering multiple quays, which employs fuzzy logic to solve the problem (Lujan et al., 2021). However, the authors of that study conclude that their approach is feasible only for small instances and suggest the use of metaheuristics for solving medium and large-size problems.

In this study, we explore the utilization of the cuckoo search algorithm (CSA) to address the multi-quay combined BAP and QCAP to alleviate the overall service cost of ships, encompassing handling cost, waiting costs, penalties for late departure, and penalties due to non-optimal berth/quay assignment. Furthermore, an appropriate mixed integer linear programming model is established for this problem, which is subsequently solved using both the exact mathematical approach and the proposed CSA. Preliminary results employing a real dataset from the Port of Limassol, Cyprus demonstrate the efficacy of the proposed CSA method, as compared to the exact method.

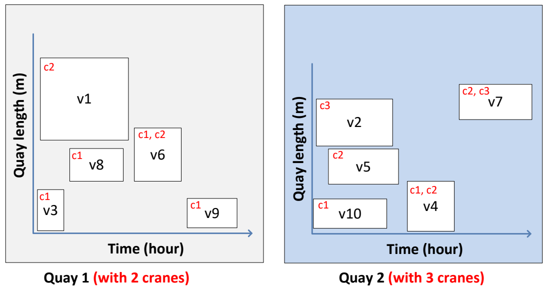

Figure 1: Combined BAP and QCAP solution with two berthing quays (both are continuous) and 10 arriving ships.

The rest of the paper is organized as follows. Section 2 provides the problem description and mathematical formulation. Section 3 presents the developed CSA method, while Section 4 shows the simulation results from the case study at the Port of Limassol, Cyprus. Section 5 concludes the study.

2 PROBLEM FORMULATION

The considered problem is discussed in this section along with the main assumptions, followed by the mathematical formulation of the problem.

2.1 Problem Explanation

The combined BAP and QCAP is an optimization problem in which the objective is to allocate available berths and available quay cranes (QCs) across time to incoming ships to perform unloading/loading operations. An example of the solution of the problem for two quays and 10 arriving ships is shown in Fig. 1. In this research, we examine a practical configuration of a port featuring multiple quays, each equipped with a specific number of cranes. Additionally, all quays adhere to a continuous style berthing layout, allowing arriving vessels to be docked at any location along the quay. Vessels are arriving in a dynamic fash-

Table 1: Nomenclature and notations.

Name	Explanation
Notations	
AQ_v	Alternative quay for vessel v
AT_v	Expected arrival time of vessel v
BP_v	Planned berthing position of vessel v
BT_v	Planned berthing time of vessel v
C_v^h	Per hour handling cost of vessel v
C_v^w	Per hour waiting cost of vessel v
C_v^{ld}	Per hour late departure cost of vessel v
C_v^{nob}	Penalty for non-optimal berthing position of v
C_v^{noq}	Penalty for non-optimal berthing quay of v
c^{min}	Minimum berthing position served by crane c
c^{max}	Maximum berthing position served by crane c
DT_v	Expected departure time of vessel v
k_v	Set of cranes assigned to vessel v (encoded in binary form)
HT_v	Handling time of vessel v
HP_q^c	Handling productivity of crane c located on quay q
L_v	Length of vessel v
L_q	Length of quay q
LDT_v	Late departure time of vessel v
$Load_v$	Total load of vessel v
Q_v	Planned berthing quay of vessel v
SC_q^c	Service cost per hour of crane c located on quay q
PBP_v	Preferred berthing position of vessel v
PBQ_v	Preferred quay of vessel v
SD	Safety distance between the berthing positions of two ships
SE	Safety port entrance time between consecutive berthings
ST	Safety time between the berthing times of two ships
WT_v	Waiting time of vessel v
Sets and Indices	
V	Set of arriving vessels; $v \in V$ a vessel
Q	Set of quays; $q \in Q$ a quay
$B(q)$	Set of available berth positions on quay $q \in Q$; $b \in B(q)$ a berth position
$C(q)$	Set of quay cranes on quay $q \in Q$; $c \in C(q)$ a crane
$K(q)$	Power set of cranes set $C(q)$; $k \in K(q)$ represents a subset of cranes from $C(q)$ encoded in a binary form
T	Set of time periods (planing horizon); $t \in T$ a time period

ion; however, their expected arrival times are known in advance. The installed QCs perform loading and unloading operations with some average productivity, which can be different for each QC.

This study considers that the following information is known in advance: number of ships, quays, and lengths of quays; estimated times of arrival and departure for each vessel; preferred berthing quay and position for each vessel; the planning horizon (which is divided into equal time intervals); and all costs and penalties. In addition, the vessels cannot change their berthing position during loading/unloading (i.e., berth shifting is not considered).

2.2 Mathematical Formulation for Multi-Quay Combined BAP and QCAP

The primary objective of the multi-quay combined BAP and QCAP is to allocate optimal berthing positions at the preferred quays, berthing times, and QCs to arriving vessels in order to reduce the total service cost (that is the combination of handling cost, waiting costs, and several penalties), as shown in the below cost function:

$$Cost\,(v, Q_v, BP_v, k_v, BT_v) = HT_v \cdot [C_v^h + f(v, Q_v, BP_v)] + WT_v \cdot C_v^w + LDT_v \cdot C_v^{ld}. \tag{1}$$

The first term of the cost function calculates the total handling cost based on the handling time HT_v (in hours), the handling cost per hour C_v^h, and a penalty function $f(.)$ for assigning additional cost to non-optimal quay and/or berth assignments. In this study, the handling time is calculated based on the total load of the vessel v and the handling productivity of the cranes assigned to v. The second term in (1) calculates the total waiting cost and it depends on the total waiting time WT_v of vessel v and the per hour waiting cost C_v^w. The waiting time WT_v of any vessel v is the difference between berthing time BT_v and arrival time AT_v. The last term in (1) calculates the penalty cost due to late departures, which is based on the late departure time LDT_v and the per hour penalty for late departure C_v^{ld}. The late departure time is non-zero when the berthing time BT_v plus the handling time HT_v exceeds the planned departure time DT_v.
The primary goal of this work is to address the combined BAP and QCAP within a multi-quay setting, aiming to minimize the overall cost encompassing handling costs, waiting costs, and various penalties. The objective function is expressed by the following

equation,

$$\textbf{minimize} \sum_{v \in V} \sum_{q \in Q} \sum_{b \in B(q)} \sum_{k \in K(q)} \sum_{t \in T} Cost(v,q,b,k,t) \cdot x_{vqbkt}, \tag{2}$$

subject to the following constraints:

$$x_{vqbkt} \in \{0,1\}, \forall\, v \in V, q \in Q, b \in B(q), k \in K(q), t \in T \tag{3}$$

$$\sum_{q \in Q} \sum_{b \in B(q)} \sum_{k \in K(q)} \sum_{t \in T} x_{vqbkt} = 1, \quad \forall\, v \in V \tag{4}$$

$$BT_v \geq AT_v, \quad \forall\, v \in V \tag{5}$$

$$BT_v - BT_u \geq SE \quad \forall\, v \neq u \in V \tag{6}$$

$$BP_v + L_v \leq L_q, \quad \forall\, v \in V,\ q = Q_v \tag{7}$$

$$\sum_{v \neq u \in V} \sum_{b=BP_v-L_u-SD}^{BP_v+L_v+SD} \sum_{k \in K(q)} \sum_{t=BT_v-HT_u-ST+1}^{BT_v+HT_v+ST-1} x_{uqbkt} = 0, \quad \forall\, v \neq u \in V,\ q = Q_v = Q_u \tag{8}$$

$$\sum_{v \neq u \in V} \sum_{b \in B(q)} \sum_{\substack{k \in K(q) \\ k\ \&\ k_v \neq 0}} \sum_{t=BT_v-HT_u-ST+1}^{BT_v+HT_v+ST-1} x_{uqbkt} = 0, \quad \forall\, v \neq u \in V,\ q = Q_v = Q_u \tag{9}$$

$$c^{min} < BP_v + L_v\ \&\ BP_v < c^{max}, \ \forall\, v \in V,\ c \in k_v \tag{10}$$

The variable x_{vqbkt} mentioned in constraint (3) takes a value of 1 if vessel v is moored at berthing position b of quay q at time t to be served by cranes k, and 0 otherwise. Constraint (4) ensures that each arriving vessel is docked only once. In constraint (5), it is stipulated that the scheduled berthing time BT_v for a vessel v must always be equal to or greater than its arrival time AT_v. The constraint (6) guarantees a minimum safety entrance time (SE) between any two consecutive berthing operations. Constraint (7) ensures the length of vessel v plus its berthing position does not exceed the length of quay q, where it is moored. Constraint (8) restricts two vessels from overlapping during mooring, both in terms of berthing positions, as well as berthing times. Furthermore, it also ensures a safety time (ST) and safety distance (SD) between the berthing of two ships. Constraint (9) restricts the set of cranes k that is assigned to vessel u to not contain any of the cranes allocated to another vessel v during the same time period. Finally, constraint (10) ensures that any crane c assigned to vessel v can reach the vessel by checking that there is an overlap between the minimum and maximum berthing positions served by c and the quay positions occupied by v.

3 CUCKOO SEARCH ALGORITHM

The cuckoo search algorithm is a relatively new nature-inspired optimization method proposed by Yang and Deb (2009) that has proven efficient in solving several global optimization problems. CSA is based on the basic rules of breeding parasitism of some cuckoo species and then extended by the so-called Levy flights Yang and Deb (2009) instead of a simple isotropic random walk (Yang and Deb, 2014). Some cuckoo birds follow an aggressive production strategy of laying eggs in communal nests and possibly removing eggs from other birds (host birds) to maximize the probability of hatching for their own eggs. When host birds discover the cuckoo eggs, hosts either discard or abandon the eggs and build new nests. Overall, the CSA operates on the basis of cuckoo reproductive behavior by following three key rules (Yang and Deb, 2009; Aslam et al., 2023):

1. one egg is dumped at a time by each cuckoo into a randomly chosen nest;
2. the nests with high-quality eggs are retained and utilized for the subsequent generation;
3. the quantity of host nests remains constant, and a host bird detects an egg laid by a cuckoo with a probability $p_\alpha \in (0,1)$.

The correspondence between CSA and the multi-quay combined BAP and QCAP is outlined as follows. A single nest represents a collection of potential solutions that include berthing times, quays, positions, and a potential set of assigned cranes for all arriving ships, as illustrated in Fig. 2. Each egg within a nest signifies either a berthing time, berthing quay, berthing position in a quay for an arriving ship, or a potential set of cranes (using binary representation). Meanwhile, a cuckoo egg represents a new or improved solution (representing either a berthing time, berthing quay, berthing position, or set of cranes).

In Fig.3, the operational flow of CSA for the multi-quay combined BAP and QCAP is depicted.

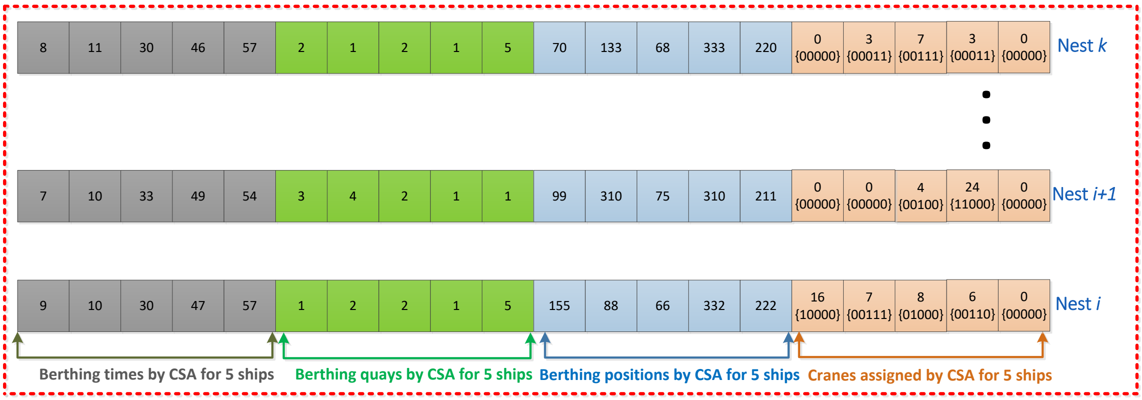

Figure 2: The representation of solutions by CSA with five ships. Each nest forms a full solution to the problem and contains five berthing times, berthing quays, berthing positions, and crane assignments, one for each ship. The binary representation of each crane assignment value denotes the set of cranes assigned to the ship.

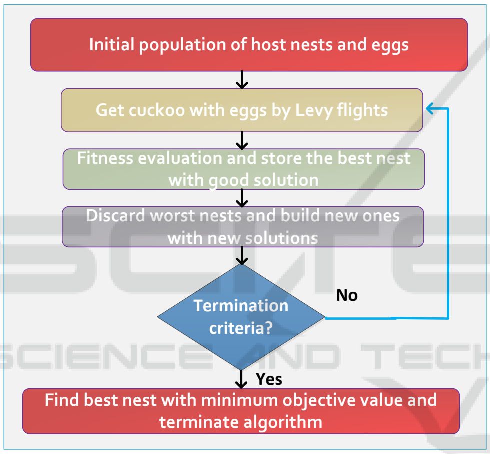

Figure 3: Flow chart of Cuckoo Search Algorithm.

The total number of host nests shows each iteration's search space, which remains constant (assuming 100 in our work). During each iteration, 100 solutions (nests) are generated, and the size of each solution is four times the total number of ships, as illustrated in Fig.2. All the solutions are compared at each iteration and the best solution (nest) is considered the local best. At the next step, some low-quality solutions (nests) are discarded and new ones are built to avoid getting stuck at local optima. Then, the fitness of new solutions is calculated and the best nest with high quality solutions is selected. All the steps are repeated until termination criteria are met (as depicted in Fig. 3).

4 CASE STUDY: PORT OF LIMASSOL, CYPRUS

A real-world case study from the Port of Limassol, Cyprus, is used to test the performance of the proposed CSA-based approach for combined berth and quay crane allocation to ships arriving during the first week of March 2018 (some example data for 10 of the ships is presented in Table 2). In the Port of Limassol, there are five commercial berthing quays, all of which are continuous. All quays are of different lengths; Container Quay: 800m; Ro-Ro Quay: 450m; West Quay: 770m; North Quay: 430m; and East Quay: 480m. There are only two container quays, i.e., the Container Quay and the Ro-Ro Quay, and a total of seven cranes are installed at both quays (5 at the Container Quay and 2 at Ro-Ro Quay). In addition, the Container Quay is further divided into two parts; two cranes operate on the left side, while the remaining three cranes operate on the right side; note there is a dead space in between the two parts of the container quay. It should also be noted that the cranes can only move within a certain range from their location. Furthermore, the cranes cannot cross each other and all have different handling productivity rates which are known.

The newly developed methods for multi-quay combined BAP and QCAP have been implemented in MATLAB R2021b. All experiments are performed using a Windows 10 computer system with a 3.4 GHz Core i7 and 16 GB RAM.

Fig. 4 and Fig. 5 show the solutions proposed by CSA and MILP, respectively, for the allocation of berths and quay cranes. The rectangles in the figures show each vessel, designating the berthing time

Table 2: Example dataset for 10 out of 28 ships that arrived at the Port of Limassol, Cyprus during the first week of March 2018.

Ship #	ETA (day\time)	HT (min.)	ETD (day\time)	PBQ	ABQ	PBP	LoS (m)
1	1\04:00	919	1\22:30	Ro-Ro Quay	Container Quay	240	194
2	1\05:30	1490	2\06:50	East Quay	–	276	139
3	1\14:00	1285	2\12:50	West Quay	North Quay	84	84
4	1\15:00	5700	5\14:03	East Quay	–	51	89
5	1\17:00	5970	5\21:00	West Quay	North Quay	314	190
6	2\04:30	470	2\13:50	Ro-Ro Quay	Container Quay	138	159
7	2\05:00	168	2\09:30	Container Quay	Ro-Ro Quay	571	196
8	2\08:00	440	2\15:55	North Quay	West Quay	53	155
9	3\04:00	905	3\20:50	Ro-Ro Quay	Container Quay	31	175
10	3\03:30	1331	4\06:15	Container Quay	Ro-Ro Quay	389	277

at the x-axis, and the berthing position of each vessel at the y-axis. The number in front of the rectangle shows the ship index and the text in green color shows the assigned set of cranes to each vessel. In addition, ships with blue rectangles indicate that they are moored at their preferred berthing quay (PBQ), while ships moored in their alternate berthing quay (ABQ) are colored red. Vessels are moored in the ABQ typically when there is a long waiting time before the optimal berth assignment, which may result in delayed departures and increased cost. From Fig. 5 it can be seen that vessel 23 is moored at the North Quay (ABQ) instead of the West Quay (PBQ) when MILP is used. On the other hand, CSA places vessel 23 at its PBQ but at the expense of placing both vessels 21 and 23 far from their preferred berthing position (PBP), thereby increasing the total service cost. It is also important to note that there are only two quays where QCs are installed and assigned; the remaining quays are passenger/general cargo quays and no cranes are installed on these quays. For container quays, the total operating time of the vessels is calculated based on the number of cranes used and their productivity. However, in the case of the other three quays, the total operating time of the vessels is provided as an input. In a week, four ships arrive at the Container Quay and six ships at the Ro-Ro Quay, all of which are assigned the optimal number of cranes using both implemented algorithms.

An in-depth comparison of the proposed method CSA with the exact MILP method is provided in Table 3 in terms of the different costs and computation time for the one-week tested scenario. Waiting costs are incurred when a vessel v has to wait before the optimal berth allocation, while NOB costs are included in the total service cost when a vessel v is berthed at a place other than its PBP or at the ABQ instead of the PBQ. NOB is calculated by determining the absolute difference between the optimal and the assigned berthing positions, as determined by any algorithm. However,

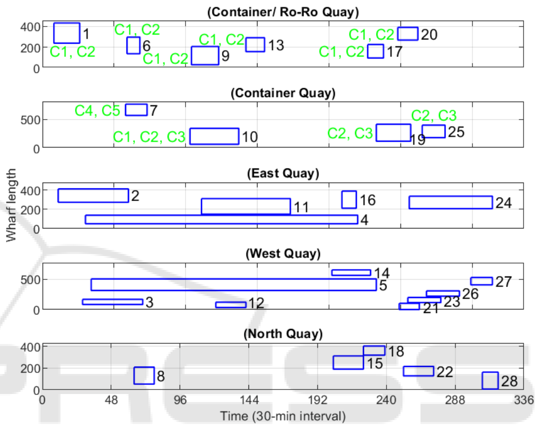

Figure 4: Solution by CSA.

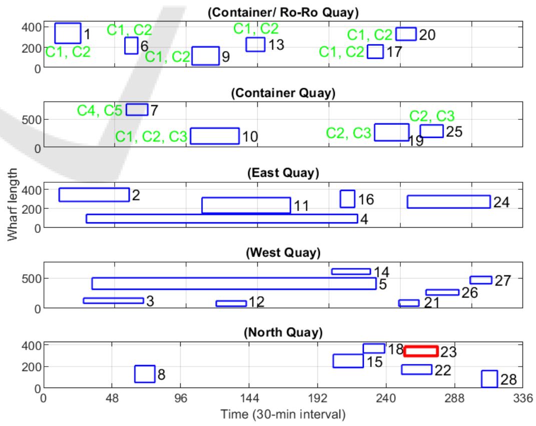

Figure 5: Solution by MILP.

a fixed penalty is added in case of berth allocation at the ABQ. Furthermore, to avoid the berthing of vessels to quays other than the ABQ or the PBQ, a penalty of infinity is added. From this table, it can be seen that MILP has a minimum total cost (10090) with 0 waiting cost and 120 cost for late departures. However, it provides an optimal solution at the ex-

Table 3: Comparative analysis of CSA and MILP.

Algorithms:	CSA	MILP
Waiting cost (€)	50	0
NOB cost (€)	250	100
Normal handling cost (€)	9870	9870
Late departure cost (€)	140	120
Total service cost (€)	10320	10090
Computation time (sec)	84.73	912.55

pense of increased computation time, which is 912.55 seconds (more than 15 minutes) for the one-week scenario. On the other hand, the total service cost for CSA is near-optimal (10320) and closely resembles MILP. However, CSA solves the problem in just 84.73 seconds, a 10× performance improvement. Note that for larger problem instances (i.e., more ships or increased planning horizon) using MILP becomes prohibitive due to the exponentially growing complexity of the problem. Based on the aforementioned comparative analysis and discussion, it can be inferred that the recently developed CSA-based approach for the multi-quay combined BAP and QCAP is highly effective and capable of delivering a solution that is close to optimal within a reasonable computation time.

5 CONCLUSIONS

This study investigates the multi-quay combined berth allocation problem (BAP) and quay crane allocation problem (QCAP) with the objective of minimizing the total service cost for arriving vessels. To solve the multi-quay combined BAP and QCAP, a MILP model is formulated and solved using both an exact method and our developed metaheuristic solution based on the cuckoo search algorithm (CSA). Evaluation results using real data from the Port of Limassol, Cyprus, confirmed the efficiency of the CSA, as compared to the exact method (MILP), since it was able to provide near-optimal results for the tested scenario at a fraction of the computation time. The MILP takes too much time (912.55 seconds) to solve the problem; however, the CSA method solves the same problem in only 84.73 seconds and the achieved objective value (10320) is only 1.02% away from the optimal solution (10090 euro). This makes the CSA method more suitable for addressing real-world problems with increased complexity where using the MILP becomes prohibitive.

The future plan is to further evaluate CSA's performance for larger problem instances of the multi-quay combined BAP and QCAP (with a larger number of ships and/or planning horizon). We also plan to implement and compare other popular computational intelligence methods such as genetic algorithm and particle swarm optimization.

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