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ORIGINAL RESEARCH

Integrated berth allocation and quay crane assignment under cooperation among multiple container terminals

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Abstract

As international trade thrives, terminal operators attempt to increase productivity to satisfy the growing demand and offer better services for customers. Cooperation among multiple terminal operators in a port is an option to better utilise the existing resources and achieve a high level of service without additional capital investment. To achieve an effective and efficient operation under cooperation, this study investigates a joint problem of berth allocation and quay crane assignment considering coordinated operation among multiple terminals in a port. Mixed-integer linear programming model considering operational constraints is developed to minimise the total operation cost, including the delay cost of vessels, transshipment cost of export containers and crane assignment cost. An adaptive large neighbourhood search algorithm is proposed to solve the integer linear programming model and tested in a series of numerical experiments. Numerical results show that cooperation not only helps to reduce the total operation cost significantly but also increases the level of service by reducing the number of delayed vessels and their total delay time. Moreover, the proposed algorithm outperforms the commercial solver, Gurobi, with better convergence results and less computational time, which enables the proposed algorithm to be applied to large-scale real-world problems.

Keywords Berth allocation · Quay crane assignment · Adaptive large neighbourhood search · Cooperation · Container terminal

1 Introduction

Global containerized trade kept rising over the decade, which reached nearly 165 million Twenty-feet Equivalent Units (TEUs) in 2021. Moreover, the share of container-based trade in the international seaborne trade increased from around 5.0% in 2000 to 18.2% in 2021 (UNCTAD, 2022). With fast-growing containerized trade, the container flow in and out of container terminals has increased significantly. The growing container throughput with handling demand fluctuation and varieties of disruptions such as COVID-19's impact bring significant uncertainties to the port operation, which motivates the container operators to better

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Extended author information available on the last page of the article utilise the port resources through the management process. To satisfy the growing demand and offer better services to customers, terminals' handling capacity and productivity need significant improvement, including upgrading existing equipment and facilities, developing new infrastructures, and so on, which usually results in high capital investment (Petering & Murty, 2009). Moreover, the limited land and quayside resources restrict the deployment of new facilities and infrastructures and further set limitations on the improvement of handling capacity and productivity. Therefore, it is vital and necessary for container terminal operators to seek feasible and efficient management solutions to increasing the handling capacity and productivity using existing resources.

Cooperation among multiple operators under coordinated operation becomes more and more popular to maximise the utilisation of existing resources and achieve higher productivity and efficiency without yielding extra capital investment in facilities and equipment. Such coordinated solutions have been applied to solving various operational problems in port operation. For instance, Imai et al. (2008b) studied the problem of berth allocation at a multi-user container terminal, where vessels could be diverted to an external terminal. Ma et al. (2020) pointed out that resource sharing between terminals in a port could reduce operation costs and improve service quality. Kavirathna et al. (2019) discussed both competition and cooperation among terminal operators in a port with a theoretical approach. Later, they extended their work to an operational level by considering cooperation with a vessel transfer policy among terminals in a port. The proposed model was tested using the port of Colombo in Sri Lanka, and the results showed that cooperation could generate profit and increase the efficiency of the ports (Kavirathna et al., 2020). These studies assumed that container terminals could cooperate on sharing handling resources by transferring vessels between each other. Terminals that divert out vessels can provide better services to the remaining ships, reducing vessel congestion and delays. Meanwhile, terminals that accept incoming vessels can better utilise their resources to obtain more profits by handling extra containers. However, diverting out vessels or accommodating incoming vessels would require terminal operators to make decisions on which vessels to divert out or in, which would significantly affect the level of service of each terminal. Moreover, it is important for terminal operators to develop effective solutions to challenging resources assignment problems, such as the integrated berth allocation and quay crane assignment. Therefore, it is necessary to investigate the resource assignment problem, considering cooperation among terminal operators to decide on diverting out/in vessels and developing an effective handling plan for each terminal.

Although container terminal operation has been widely studied in the literature, limited studies have taken cooperation among multiple terminals into account. Moreover, cooperative operation has been investigated in the policy level (such as vessel transfer) and with a focus on the berth allocation problem only, but not in the joint problem of berth allocation and quay crane assignment, which is among the most important container terminal planning problems on quayside operations. To fill the research gap, this paper aims to investigate the joint problem of berth allocation and quay crane assignment considering the coordinated operation of multiple container terminals in a port. The arrival vessels can be served at any terminal in the port when cooperation among operators is considered.

The major contribution of this paper is summarised as below. First, a new model of the joint problem of berth allocation and quay crane assignment under cooperation among multiple container terminals in a port is proposed with consideration of various practical constraints, such as different water depths and transshipment costs of export containers between quays. Second, an adaptive large neighbourhood search (ALNS) algorithm embedded with tailored remove and repair operators is developed with better performance than commercial solvers such as Gurobi on computational time and convergence. Promising numerical results are achieved based on both benchmark experiments in literature and random-generated complex cases. Thirdly, comprehensive numerical studies analyse the benefits of cooperation regarding the delay time and total cost, and the effects of transshipment cost. The numerical results further highlight the benefits of cooperation and provide a valuable reference for cooperation among terminal operators.

The remainder of this paper is organised as follows: Sect. 2 reviews the relevant literature; An integer linear programming model considering different water depths of terminals and other operational constraints is formulated in Sect. 3, followed by the solution approach introduced in Sect. 4; In Sect. 5, numerical experiments based on different instances are conducted to evaluate the proposed approach's performance; Sect. 6 concludes this study with a discussion of future research direction.

2 Literature review

Berths and quay cranes are among the most important resources to enable daily operation in container terminals, which have attracted significant research efforts over the decades, both on the berth allocation and quay crane management problems separately and jointly.

The berth allocation problem (BAP) aims to determine when and where the arrival vessels should be berthed. Imai et al. (2001) firstly formulated the dynamic BAP, which assumed that the vessels would arrive one after another in the dynamic BAP version. Later, various methods were developed to solve the dynamic BAP for both continuous and discrete cases (Wawrzyniak et al., 2020). BAP is also incorporated with various factors, such as fuel consumption (Du et al., 2011), priority control (Ursavas, 2015), uncertain handling times(Guo et al., 2021) and so on. Limited studies have investigated BAP with multiple continuous quays or cooperation among terminals. Imai et al. (2008b) studied the BAP considering diverting vessels to an external terminal and assumed that the external terminal would charge the terminal operator based on the total handling time of diverted vessels. As an extended work, Dulebenets et al. (2018) assumed that the diverted vessels could only be served at the external terminal during available time windows. Xu et al. (2021) proposed a collaborative mechanism based on price adjustment and transfer payment, which allowed the different terminal operators to cooperate on berth scheduling under emergency. Some papers considered cooperation among multiple quays, which is similar to the coordinated version. Frojan et al. (2015) investigated berth allocation among multiple quays, and genetic algorithm (GA) and local search were employed to solve the model. Ma et al. (2019) investigated a joint problem of berth allocation and yard planning among multiple quays with the handling time of vessels given in advance. However, in reality, the handling time of vessels usually depends on the quay crane assignment. Cheimanoff et al. (2022b) proposed an iterated local search-based (ILS) approach to investigate the continuous BAP with multiple continuous quays in tidal bulk terminals. Guo et al. (2022) investigated the discrete BAP incorporated with berth assignment considering cooperation between liner carriers. It is assumed that all dedicated berths are rentable to each liner. Later, Guo et al. (2023) proposed a two-stage framework to investigate the BAP among neighbouring ports, where the first stage optimised berth allocation plan and the second stage groups neighbouring ports into different groups to form stable cooperation based on the decision of the first stage.

The joint problem of berth allocation and quay crane assignment (BAQCAP) was first proposed by Park and Kim (2003). A two-phase solution procedure was proposed to determine the berth positions and the number of quay cranes (QCs) assigned to vessels with subgradient optimisation used in the first stage, and then dynamic programming was adopted to assign the QCs to each vessel. Imai et al. (2008a) conducted research on discrete BAQCAP and employed a genetic algorithm to determine the berth position and QC scheduling simultaneously. Considering the increase of handling time at undesired positions and the decrease of marginal productivity of QC assigned to a vessel, Meisel and Bierwirth (2009) reformulated the BAQCAP and utilised squeaky wheel optimisation with Tabu search (TS) to solve the problem. Iris et al. (2015) extended the model and presented two generalised set partitioning models for BAQCAP with time-variant and time-invariant QC profiles, respectively. In follow-up work, Iris et al. (2017) improved their model and designed an ALNS heuristic for the BAQCAP. Based on the rolling-horizon approach, Chang et al. (2010) formulated the BAQCAP as a dynamic allocation model and a hybrid parallel GA was employed to solve the model. Giallombardo et al. (2010) proposed the concept of QC profile and presented two formulations, a mixed-integer quadratic program and a mixed-integer linear program, for the BAQCAP in the transshipment terminal. A heuristic algorithm based on TS was developed to solve the BAQCAP. Later, Xie et al. (2018) extended the model to a conventional container terminal, and a branch and price algorithm was developed to obtain the exact solution. Moreover, several studies have investigated the BAQCAP with consideration of different factors and constraints. Cheimanoff et al. (2022a) studied the BAP and time-invariant QCAP problem. A novel mixed-integer linear formulation (MILP) and a Variable Neighborhood Search (VNS) were proposed to solve the model. Moreover, several studies have investigated the BAQCAP with consideration of different factors and constraints. Hu et al. (2014) studied the BAQCAP considering carbon emission taxation, and a bi-objective model was formulated to help terminal operators make trade-off between fuel consumption and port operational cost. Li et al. (2015) addressed the continuous BAQCAP with consideration of QC coverage range and proposed a heuristic algorithm based on spatio-temporal conflict analysis. Zhen et al. (2017) considered the tides and channel flow control constraints, and a column generation based approach was employed to solve the model. Similarly, Malekahmadi et al. (2020) studied the BAP and QC scheduling problem considering water depth and tide conditions and proposed a particle swarm optimization algorithm to solve the large-scale instances. Some scholars focused on handling the uncertainties during the terminal operation, such as uncertain handling time and disruptions. Tan and He (2021) developed a scenario-based mathematical model for BAQCAP considering uncertain vessels' arrival times and handling demand and solved the model with two-stage heuristics framework. Similarly, Rodrigues and Agra (2021) studied the BAQCAP considering the uncertain arrival times and proposed an exact decomposition algorithm to solve the scenario-based model. Wang et al. (2023) investigated the BAQCAP with uncertain arrival time and operation time through the scenario-based model to resist various disruptions. A more comprehensive review of BAQCAP under uncertainty can be referred to Rodrigues and Agra (2022). Furthermore, the BAQACP was integrated with other resource operations, such as green energy resources (Chargui et al., 2023) and waterway scheduling (Fatemi-Anaraki et al., 2021).

Although both BAP and QCAP have been widely investigated, to the best of our knowledge, none of the studies has investigated the BAPQACP considering coordinated operation among different container terminals in a port. Only a few studies investigated the BAP with consideration of cooperation among terminal operators. The handling time of vessels is usually given in advance. However, in reality, the handling time of vessels usually depends on the quay crane assignment. In addition, different quays usually have different water depths, and the number of diverted vessels is limited. Moreover, the transportation cost between two quays of export containers due to diverted service was not considered in most studies. Inspired by the aforementioned research gap, this study aims to address the BAQACP with consideration of multi-terminal cooperation in a port. As a closely relevant work, Tasoglu and Yildiz (2019) studied the joint problem of BAQCAP and QCSP considering quay discontinuities in the same terminal. However, the increase in handling time at undesired positions and interference between QCs were not considered. Different from the literature studies, multiple practical constraints, such as different water depths and transshipment costs of export containers between quays are considered in this study. Table 1 summarises the relevant studies in terms of the addressed problems and the solution methods.

3 Model formulation

3.1 Problem description and notations

In this study, we consider a port consisting of multiple container terminals with a given length of each quay, the number of quay cranes and water depth. Terminals are operated by different operators but under the same management company. For example, there are four container terminals (Tanjong Pagar Terminal, Keppel Terminal, Brani Terminal and Pasir Panjang Terminal) in Singapore controlled by PSA Singapore (PSA Singapore, 2020). Different terminals are located at different places with their own yards. An illustration of terminal layout in a port with multiple quays is shown in Fig. 1.

Given a set of container vessels with known characteristics, such as length, draft, arrival time, handling demand, desired departure time, scheduled terminal and desired position at each quay, this study aims to assign a terminal, a berthing position and a time-variant quay crane assignment profile to each vessel over a given time horizon. A quay crane assignment profile represents the number of QCs assigned to a vessel at each time during its service time. A vessel reports its expected arrival time and desired departure time to the container terminal operator before its arrival. Subsequently, terminal operators develop a berth plan for each vessel, including the berth position, berth time and QC profile. In this study, a vessel's scheduled terminal can be changed to any other terminal within the port as long as its draft restriction is satisfied. Moreover, it is assumed that both export and import containers will be stored at the scheduled terminal. Therefore, changing a vessel's mooring terminal will result in extra container transshipment costs.

According to Meisel and Bierwirth (2009), the transportation distance from the yard to the quayside increases when a vessel does not berth at its desired position, thus, more QC hours are needed to complete the cargo loading and unloading. In this study, the increase

Table 1 Summary of the related work

Problem	Features			Reference	Solution method
	Berth layout	Number of quays	Cooperation		
BAP	Continuous berth	Single		Du et al. (2011)	Commerical solver
		Multiple		Cheimanoff et al. (2022b)	Iterated local search
	Discrete berth	Single		Imai et al. (2001)	Subgradient method
		Single		Ursavas (2015)	Simulation with GA
		Single		Guo et al. (2021)	Particle swarm optimization
		Multiple	✓	Imai et al. (2008b)	Genetic algorithm
		Multiple	✓	Dulebenets et al. (2018)	Memetic algorithm
		Multiple	✓	Xu et al. (2021)	Commercial solver
		Multiple		Guo et al. (2022)	Genetic algorithm
	Hybrid berth	Single		Frojan et al. (2015)	Genetic algorithm
	Irregular berth	Single		Ma et al. (2019)	Guided neighbourhood search
BAQCAP	Discrete berth	Single		Imai et al. (2008a)	Genetic algorithm
		Single		Giallombardo et al. (2010)	Tabu search and MIP
		Single		Zhen et al. (2017)	Column generation based approach
		Single		Xie et al. (2018)	Branch and price
		Single		Chargui et al. (2023)	Robust exact decomposition
	Continuous berth	Single		Park and Kim (2003)	Lagrangian relaxation
		Single		Meisel and Bierwirth (2009)	Squeaky wheel optimization
		Single		Chang et al. (2010)	Parallel genetic algorithm
		Single		Hu et al. (2014)	Heuristic and solver
		Single		Li et al. (2015)	Heuristic
		Single		Iris et al. (2015)	Set partitioning model with column reduction
		Single		Iris et al. (2017)	Enhanced MILP and ALNS
		Multiple		Tasoglu and Yildiz (2019)	Simulated annealing-based simulatio
		Single		Malekahmadi et al. (2020)	Particle swarm optimization
		Single		Fatemi-Anaraki et al. (2021)	Meta-heuristics
		Single		Tan and He (2021)	Two-stagemeta-heuristic
		Single		Rodrigues and Agra (2021)	Decomposition algorithm
		Single		Cheimanoff et al. (2022a)	Variable Neighborhood Search
		Single		Wang et al. (2023)	Column and constraint generation
		Multiple	✓	This paper	ALNS

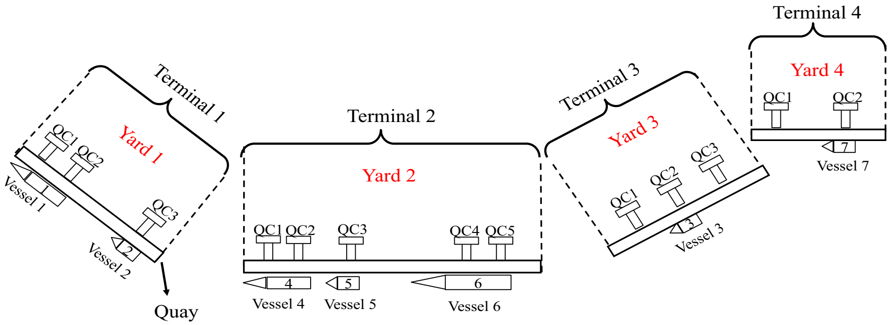


Fig. 1 A sample layout of terminals in a port with multiple quays

in handling time at the undesired position and the interference between QCs are taken into account. As defined in most literature studies, each vessel has an upper and a lower limit on the number of assignable QCs, respectively, which are limited by the size of the vessel and the contract between the ship owner and the operator. It is assumed that each vessel's berth position is fixed until cargo loading and unloading from the vessel is completed.

Besides the general assumptions in Meisel and Bierwirth (2009), the following additional assumptions are considered:

(1) Changing a vessel's mooring terminal will result in extra container transshipment costs considering that export containers stored at the original scheduled terminal need to be transported to the actual calling terminal.

(2) There is still a desired berth position at the actual calling terminal if the vessel changes the calling terminal. This is because the export container will be transferred to a dedicated area due to the limitation of yard spaces and the original scheduled yard storage plan.

The following notations are introduced for the model development in the subsequent sections (Table 2).

3.2 Terminal assignment under cooperation

The BAQCAP under cooperation needs to assign vessels to appropriate terminals first with consideration of the water depth constraint. It is assumed that a vessel can only berth at one terminal to complete loading and unloading of cargoes. Therefore, the following constraint is given to ensure that each vessel can be assigned to only one terminal.

$$\sum_{p\in P} y_i^p = 1, \forall i \in V; \tag{1}$$

$$d_i \leq (1 - y_i^p)M + W^p, \forall p \in P, i \in V \tag{2}$$

Since the export containers are stored at the original terminal where the vessel will be moored, diverting vessels to other terminals would result in transshipment cost. It is assumed that both the import and export containers will be stored at the original terminals. Therefore, the total transshipment cost of containers J_1 for all terminals can be represented as follows:

Table 2 List of notations

Parameters	
P	set of terminals, $p \in P$
V	set of vessels, $i \in V$
V_p	set of vessels designated to terminal *p*, $p \in P$
Q^p	set of quay cranes of terminal *p*
T	planning horizon, $t \in T$
W^p	water depth of terminal *p*
L^p	length of terminal *p*
b_i^p	desired berthing position of vessel *i* at terminal *p*
d_i	draft of vessel *i*
l_i	length of vessel *i*
s_i	scheduled terminal of vessel *i*
h^{load}	handling rate of unit QC per hour
QC_i	total QC-hour demand of vessel *i*
r_i^{min}	minimum number of QCs assigned to serve vessel *i*
r_i^{max}	maximum number of QCs assigned to serve vessel *i*
r_i	range of the number of QCs can be assigned to vessel *i*, $r_i = [r_i^{min}, r_i^{max}]$
ETA_i	expected arrival time of vessel *i*
EST_i	earliest start time of vessel *i*, $EST_i \leq ETA_i$
EFT_i	expected finishing time of vessel *i*
LFT_i	latest finishing time of vessel *i*, $LFT_i \geq EFT_i$
c_i^1	speed up cost for arriving earlier than ETA_i of vessel *i*
c_i^2	cost of exceeding the expected finishing time EFT_i for vessel *i*
c_i^3	penalty cost for exceeding the latest finishing time LFT_i for vessel *i*
c^4	operating cost of a QC per hour
$c^{p'p}$	transshipment cost per TEU between terminals *p* and *p′*
α	interference exponent of QC's operation
β	berth deviation factor
M	a large positive constant
Decision variables	
x_i	berth position of vessel *i*
y_i^p	1 if vessel *i* is berthed at terminal *p*; 0 otherwise
t_i^b	berthing time of vessel *i*
t_i^d	actual departure time of vessel *i*
η_{ij}^p	1 if vessel *i* is berthed to the left side of vessel *j* at terminal *p*; 0 otherwise
r_{qit}^p	1 if *q* QCs are assigned to vessel *i* at terminal *p* at time period *t*; 0 otherwise
θ_{ij}^p	1 if the departure time of vessel *i* is no later than the starting time of handling vessel *j* at terminal *p*
r_{it}^p	1 if at least one QC is assigned to vessel *i* at terminal *p* at time period *t*; 0 otherwise
Auxiliary variables	
$\tilde{t}_i^d$	departure delay time of vessel *i*
$\tilde{t}_i^b$	speed up time of vessel *i* to reach its berthing time
ρ_i	1 if the finishing time of vessel *i* exceeds LFT_i; 0 otherwise
μ_i	the deviation of vessel *i* between the its desired and actual berth position

$$J_1 = \sum_{i \in V} \sum_{p \in P} y_i^p C_i^{load} c^{s_i p} \tag{3}$$

3.3 Berth allocation and quay crane assignment (BAQCAP)

After assigning vessels to terminals, each terminal needs to make a detailed berthing plan for the arriving vessels. A sample berthing plan of six vessels (vessels 1-5 and *i*) in a terminal is illustrated in a time-space diagram, as shown in Fig. 2. Each vessel is represented by a rectangle that shows the berthing position and the vessel's time duration. Moreover, relevant parameters are shown in Fig. 2 taking vessel *i* for instance. For example, the handling time of vessel *i* is six time units. Five QCs are assigned to vessel *i* in the first time unit, four QCs are assigned in the fourth and last time units, and three QCs are assigned for each of the rest time units. The starting point of the berthing area of vessel *i* is the berthing positioning.

According to Meisel and Bierwirth (2009), vessel *i* needs to report its expected arrival time ETA_i, earliest start time EST_i, expected EFT_i and latest departure time LFT_i to the terminal operator when it is going to berth at a terminal. The terminal will then make a berthing plan for vessel *i*, including the berthing time, berthing position, and QC assignment. Therefore, vessel *i* will not be moored earlier than EST_i, thus we have:

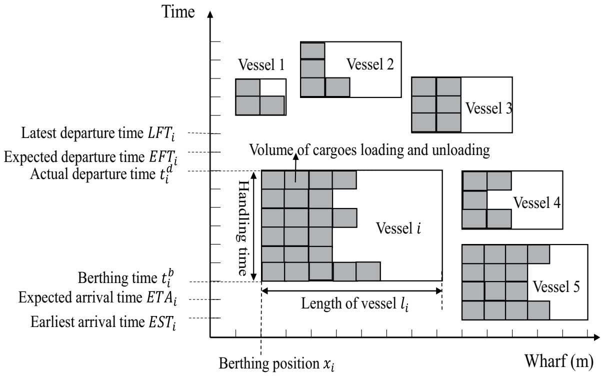
$$t_i^b \geq EST_i, \forall i \in V \tag{4}$$

If the berthing time of vessel *i* is earlier than ETA_i, vessel *i* needs to speed up to catch the berthing plan, which will result in speed-up cost. The speed-up cost grows constantly in time. Similarly, when the departure time of vessel *i* is later than EFT_i, delay cost occurs and grows constantly over time. Moreover, penalty cost will incur if the departure time exceeds the LFT_i. Penalty cost will be counted once for each vessel. Thus, we have the following constraints to calculate the delay time and speed-up time, and judge whether it finishes the mooring later than the required latest time of each vessel:

$$\tilde{t}_i^b \geq ETA_i - t_i^b, \forall i \in V \tag{5}$$

$$\tilde{t}_i^d \geq t_i^d - EFT_i, \forall i \in V \tag{6}$$

Fig. 2 A sample of berthing plan in time-space diagram in a terminal



$$t_i^d \leq LFT_i + \rho_i M, \forall i \in V \tag{7}$$

Generally, it is assumed that there is a desired berthing position b_i^p for vessel *i* at terminal *p*, which is specified for vessel *i* within the vicinity of these yard areas. When the actual berthing position is apart from the desired position, vehicles are needed to transport containers between the yard and quayside. Thus, the average speed of loading and unloading is decelerated, and more QC hours are needed. The deviation of berth position is calculated as follows:

$$\mu_i \geq x_i - b_i^p - (1 - y_i^p)M, \forall i \in V, p \in P \tag{8}$$

$$\mu_i \geq b_i^p - x_i - (1 - y_i^p)M, \forall i \in V, p \in P \tag{9}$$

Moreover, the berthing position of vessel *i* should not exceed the boundary of its assigned terminal, hence we have:

$$x_i \leq L^p - l_i + (1 - y_i^p)M, \forall i \in V, p \in P \tag{10}$$

Then, we make the detailed QC assignment. Firstly, no quay crane will be assigned to vessel *i* neither before its berthing nor after its departure. Quay cranes are only assigned to vessel *i* within its berthing duration. Thus,

$$tr_{it}^p + (1 - r_{it}^p)T \geq t_i^b, \forall i \in V, p \in P, t \in T \tag{11}$$

$$(t+1)r_{it}^p \leq t_i^d + (1 - r_{it}^p)T, \forall i \in V, p \in P, t \in T \tag{12}$$

$$\sum_{p \in P} \sum_{t \in T} r_{it}^p = t_i^d - t_i^b, \forall i \in V, p \in P \tag{13}$$

Moreover, no QC will be assigned to vessel *i* if it is not moored at terminal *p*, and the number of QCs should be within the range r_i.

$$r_{it}^p \leq y_i^p, \forall i \in V, t \in T, p \in P \tag{14}$$

$$\sum_{q \in r_i} r_{qit}^p = r_{it}^p, \forall i \in V, t \in T, p \in P \tag{15}$$

Given a berth position and a deviation factor β, the workload of vessel *i* is modified to $(1 + \beta\mu_i)QC_i$. With consideration of the interference between QCs with an interference coefficient α, we have:

$$\sum_{t \in T} \sum_{q \in r_i} q^\alpha r_{qit}^p \geq (1 + \beta\mu_i)QC_i - (1 - y_i^p)M, \forall i \in V, p \in P \tag{16}$$

which guarantees that the modified workload of vessel *i* should be satisfied. Obviously, the assignment of r_i^{min} results in the longest time duration of vessel *i* mooring at the assigned berth, while r_i^{max} leads to the shortest one. Therefore, the range of time duration of vessel *i* mooring at the berth can be determined by the following constraint:

$$\frac{(1+\beta\mu_i)QC_i}{(r_i^{max})^\alpha} \le t_i^d - t_i^b \le \frac{(1+\beta\mu_i)QC_i}{(r_i^{min})^\alpha}, \forall i \in V, p \in P \tag{17}$$

Furthermore, the QCs assigned to vessels at any time cannot exceed the number of available QCs at terminal *p*.

$$\sum_{i \in V} qr_{qit}^p \le Q^p, \forall t \in T, p \in P \tag{18}$$

In reality, a berthing position cannot be occupied by two or more vessels simultaneously. Therefore, the berth plan of vessel *i* should not overlap with those of other vessels. In other words, the rectangle in Fig. 2 representing the berthing plan of vessel *i* should not overlap with other rectangles. Three conditions should be met if the berthing plans of vessels *i* and *j* overlap in time and space: (1) vessels *i* and *j* are moored at the same terminal; (2) the berthing duration of vessels *i* and *j* have the same period; (3) the berthing areas of vessels *i* and *j* have the same berth section. Therefore, we can have the relationship of berthing time and position between vessels *i* and *j* as follows:

$$x_j + (1-\eta_{ij}^p)M \ge x_i + l_i, \forall i,j \in V, i \ne j, p \in P \tag{19}$$

$$t_j^b + (1-\theta_{ij}^p)M \ge t_i^d, \forall i,j \in V, i \ne j, p \in P \tag{20}$$

$$\eta_{ij}^p \le y_i^p, y_j^p, \forall i,j \in V, i \ne j, p \in P \tag{21}$$

$$\theta_{ij}^p \le y_i^p, y_j^p, \forall i,j \in V, i \ne j, p \in P \tag{22}$$

Constraint (19) reflects that the berth position of vessel *j* should be larger than that of vessel *i* plus its length if vessel *j* is berthed at the right of vessel *i*. Similarly, Constraint (20) guarantees that the berthing time of vessel *j* should be larger than the ending time of vessel *i* if vessel *i* leaves before vessel *j* berths. Constraints (21) and (22) show that there is no connection between two vessels in time and space if they are moored at different terminals. To avoid overlapped berthing plans of two vessels, we can have the following constraints:

$$\eta_{ij}^p + \theta_{ij}^p + \eta_{ji}^p + \theta_{ji}^p \ge y_i^p + y_j^p - 1, \forall i,j \in V, i \ne j, p \in P \tag{23}$$

$$\eta_{ij}^p + \theta_{ij}^p + \eta_{ji}^p + \theta_{ji}^p \le y_i^p + y_j^p, \forall i,j \in V, i \ne j, p \in P \tag{24}$$

Based on the structure of the service quality cost of a vessel developed in Meisel and Bierwirth (2009), three types of costs are considered in this paper: the speed-up cost of a vessel to catch a berthing time earlier than ETA_i, the cost of exceeding the expected finishing time EFT_i, and the penalty cost for exceeding the latest allowed finishing time LFT_i. Thus, we have the service quality cost J_2 of all vessels as follows:

$$J_2 = \sum_{i \in V} (\tilde{t}_i^b c_i^1 + \tilde{t}_i^d c_i^2 + \rho_i c_i^3) \tag{25}$$

Moreover, the cost J_3 of operating quay cranes is the fundamental cost of BAQCAP, which includes the fuel consumption and labour cost as follows:

$$J_3 = \sum_{i \in V} \sum_{p \in P} \sum_{q \in r_i} q r_{qit}^p c^4 \tag{26}$$

3.4 BAQCAP under cooperation (C-BAQCAP)

Different from minimizing the total cost of each terminal under non-coordination, BAQCAP under coordination aims to minimize the total cost of all participants under coordination, which includes the service quality cost, operating cost of QCs and transshipment cost of containers. Thus, we obtain the objective function of BAQCAP under coordination as follows:

$$\text{Min} \quad J = J_1 + J_2 + J_3 \tag{27}$$

Moreover, the binary and non-negative decision variables are given as follows:

$$r_{qit}^p, \theta_{ij}^p, \eta_{ij}^p, \rho_i, y_i^p \in \{0, 1\}, \forall i, j \in V, t \in T, q \in r_i, p \in P \tag{28}$$

$$x_i, \mu_i, \tilde{t}_i^d, \tilde{t}_i^b \geq 0, \forall i \in V, p \in P \tag{29}$$

Finally, the complete C-BAQCAP model is given as follows:

$$\text{Min} \quad J = J_1 + J_2 + J_3 \tag{30}$$

$$\sum_{p \in P} y_i^p = 1, \forall i \in V \tag{31}$$

$$d_i \leq (1 - y_i^p) M + W^p, \forall p \in P, i \in V \tag{32}$$

$$x_i \leq L^p - l_i + (1 - y_i^p) M, \forall p \in P, i \in V \tag{33}$$

$$t_i^b \geq EST_i, \forall i \in V \tag{34}$$

$$t_i^d \leq LFT_i + \rho_i M, \forall i \in V, p \in P \tag{35}$$

$$\tilde{t}_i^b \geq ETA_i - t_i^b, \forall i \in V \tag{36}$$

$$\tilde{t}_i^d \geq t_i^d - EFT_i, \forall i \in V \tag{37}$$

$$\mu_i \geq x_i - b_i^p - (1 - y_i^p)M, \forall i \in V, p \in P \tag{38}$$

$$\mu_i \geq b_i^p - x_i - (1 - y_i^p)M, \forall i \in V, p \in P \tag{39}$$

$$x_j + (1 - \eta_{ij}^p)M \geq x_i + l_i, \forall i, j \in V, i \neq j, p \in P \tag{40}$$

$$t_j^b + (1 - \theta_{ij}^p)M \geq t_i^d, \forall i, j \in V, i \neq j, p \in P \tag{41}$$

$$\eta_{ij}^p + \theta_{ij}^p + \eta_{ji}^p + \theta_{ji}^p \geq y_i^p + y_j^p - 1, \forall i, j \in V, i \neq j, p \in P \tag{42}$$

$$\eta_{ij}^p + \theta_{ij}^p + \eta_{ji}^p + \theta_{ji}^p \leq y_i^p + y_j^p, \forall i, j \in V, i \neq j, p \in P \tag{43}$$

$$\eta_{ij}^p \leq y_i^p, y_j^p, \forall i, j \in V, i \neq j, p \in P \tag{44}$$

$$\theta_{ij}^p \leq y_i^p, y_j^p, \forall i, j \in V, i \neq j, p \in P \tag{45}$$

$$\sum_{q \in r_i} r_{qit}^p = r_{it}^p, \forall i \in V, t \in T \tag{46}$$

$$\sum_{p \in P} \sum_{t \in T} r_{it}^p = t_i^d - t_i^b, \forall i \in V \tag{47}$$

$$(t+1) r_{it}^p \leq t_i^d + (1 - r_{it}^p)T, \forall i \in V, p \in P, t \in T \tag{48}$$

$$r_{it}^p \leq y_i^p, \forall i \in V, p \in P, t \in T \tag{49}$$

$$t r_{it}^p + (1 - r_{it}^p)T \geq t_i^b, \forall i \in V, p \in P, t \in T \tag{50}$$

$$\sum_{i \in V} q r_{qit}^p \leq Q^p, \forall t \in T, p \in P \tag{51}$$

$$\sum_{t \in T} \sum_{q \in r_i} q^\alpha r_{qit}^p \geq (1 + \beta\mu_i) QC_i - (1 - y_i^p)M, \forall i \in V, p \in P \tag{52}$$

$$\frac{(1 + \beta\mu_i) QC_i}{(r_i^{max})^\alpha} \leq t_i^d - t_i^b \leq \frac{(1 + \beta\mu_i) QC_i}{(r_i^{min})^\alpha}, \forall i \in V, p \in P \tag{53}$$

$$r_{qit}^p, \theta_{ij}^p, \eta_{ij}^p, \rho_i, y_i^p \in \{0, 1\}, \forall i, j \in V, t \in T, p \in P, q \in r_i \tag{54}$$

$$x_i, \mu_i, \tilde{t}_i^d, \tilde{t}_i^b \geq 0, \forall i \in V \tag{55}$$

4 Solution approach

Both BAQCAP and C-BAQCAP are difficult to solve since the BAP is NP-hard (Monaco & Sammarra, 2007). Although several studies applied genetic and memetic algorithms to solve the BAP considering cooperation, QCAP was ignored making the existing methods unsuitable for C-BAQCAP. In addition, after testing, embedding the general framework of genetic and memetic algorithms could not obtain good-quality solutions. In recent years, multiple researchers have applied the adaptive large neighbourhood search algorithm to solve BAQCAP, and the results showed its effectiveness by comparison with squeaky wheel optimization, tabu search and genetic algorithm (Mauri et al., 2016; Iris et al., 2017). Therefore, this study adopts the ALNS framework for solving the C-BAQCAP.

The ALNS algorithm was proposed by Ropke and Pisinger (2006) as an extension of the large neighbourhood search approach of Shaw (1998). The main components of an ALNS include the destroy and repair operators, adaptive mechanism, and acceptance and termination criteria. After constructing an initial solution, the ALNS destroys part of the initial solution and then repairs it with different destroy and repair operators. The destroy and repair operators are selected according to an adaptive probabilistic mechanism, and their selection probabilities are updated according to their previous performances. After a new solution is generated, an acceptance criterion is applied to judge whether the new solution is acceptable and determine whether the next step of searching starts from the current or the new solution. The above steps are iterated until the termination criterion is reached.

To solve the C-BAQCAP model efficiently, we modify the conventional ALNS by designing new operators. Given an initial solution, a destroy operator is chosen to remove λ vessels, and then a repair operator is chosen to insert the removed vessels into the current solution. In this study, each vessel is initially assigned to its scheduled terminal, and then based on the non-decreasing order of their arrival times, the initial solution is generated with the rule that each vessel berths as early as possible. Four destroy operators and four repair operators are developed in this paper, respectively, in the following subsections. Similar to Mauri et al. (2016) and Iris et al. (2017), λ is determined by generating a random integer between 2 and λ_u, wherein λ_u is determined by the size of instances multiplied by a parameter λ_r between (0, 1).

The adaptive mechanism aims to score each operator according to the performance and update the selection probability of each operator. Each operator o is assigned with an initial weight w_o and an initial score $\pi_o = 0$. In each iteration, the score of each operator will be updated according to its performance. The better the solution is, the higher the score it gets. In this study, the initial score π_o increases by σ_1 if operator o obtains the best solution among all iterations, by σ_2 if operator o obtains a better solution than the current one, and by σ_3 if operator o obtains a worse solution than the current one and this solution has not been found before while it satisfies the acceptance criteria. The selection probability w_o of each operator o will be updated after every δ iterations as follows:

$$w_o = \begin{cases} w_o & n_o = 0 \\ (1-\tau)w_o + \tau\pi_o/n_o & n_o \neq 0 \end{cases} \tag{56}$$

wherein n_o is the number of times operator o used in the last δ iterations, and τ is a parameter ranging within (0, 1].

The acceptance criteria of simulated annealing is employed in this study. If the new solution s' is better than the current one s, s' is acceptable; otherwise, s' will be accepted with probability $e^{-(f(s')-f(s))/T}$. $f(s')$ and $f(s)$ are the objective function values of s' and s, respectively, which are defined in Eq. (27). T is the current temperature, and the initial temperature T_{start} drops by $(1-\varepsilon)T_{start}, 0<\varepsilon<1$ in each iteration. Following Iris et al. (2017); we set T_{start} and the end temperature T_{end} as $\xi_1\%$ and $\xi_2\%$ of the objective function value in the initial solution, respectively. Therefore, we can obtain the cooling rate ε and the maximum iteration δ_{max} of the algorithm, and the algorithm stops once the maximum iteration δ_{max} is reached. The pseudo-code of the proposed ALNS algorithm is shown in Algorithm 1.

Algorithm 1 Pseudo code of the proposed ALNS algorithm

```
INPUT: Information of terminals and arrival vessels;
OUTPUT: Optimal berth allocation and QC assignment plan;
Generate an initial solution $s$ and calculate $f(s)$. $\pi_o = 0$, $w_o = 0$, $n_o = 0$, $T = T_{start}$, $iteration = 0$, $s_{best} = s$, $f(s_{best}) = f(s)$
while the stop criteria is not met do
    $s' \leftarrow s$, $iteration = iteration + 1$;
    Draw a random integer number $\lambda$ in $[2, \lambda_u]$;
    Choose and apply a destroy operator to removing $\lambda$ vessels from $s'$;
    Choose and apply a repair operator to insert the removed vessels back to $s'$;
    if $f(s') < f(s)$ then
        $s \leftarrow s'$, $f(s) \leftarrow f(s')$;
        if $f(s') < f(s_{best})$ then
            $s_{best} \leftarrow s'$, $f(s_{best}) \leftarrow f(s')$;
            Update the score of the chosen destroy and repair operators with $\sigma_1$
        else if  then
            $s \leftarrow s'$, $f(s) \leftarrow f(s')$;
            Update the score of the chosen destroy and repair operators with $\sigma_2$;
        end if
    else if  then
        if $s'$ is accepted by acceptance criteria then
            $s \leftarrow s'$, $f(s) \leftarrow f(s')$;
            Update the score of the chosen destroy and repair operators with $\sigma_3$
        end if
    end if
    if the remainder of $iteration/\delta$ is 0 then
        Update the weights of operators, $\pi_o = 0$, $n_o = 0$
    end if
    $T = \varepsilon T$;
end while
```

4.1 Destroy operators

Given a solution s, destroy operators aim at removing λ vessels from s. The destroy operators remove vessels from each terminal separately, and the number of the removed vessels in each terminal λ^p is a portion of λ and is determined by its total cost. The higher the total cost of the terminal, the more vessels will be removed. Let V_r^p be the set of removed vessels at terminal *p* and s^p be a partial solution at terminal *p*.

Random remove operator: This operator removes λ^p vessels from the current solution s^p randomly. Roulette selection is employed in this operator to remove the high-cost vessels with higher probabilities.

Shaw remove operator: This operator was proposed by Shaw (1998), which removes vessels with respect to several criteria. In this study, the relatedness between two vessels i and *j* is defined by the differences in berthing position and berthing time. Each criterion is weighted with a parameter χ and the relatedness *C*(*i*, *j*) for vessel *i* and *j* can be calculated as follows (Iris et al., 2017):

$$C(i,j) = \chi_a|t_i^b - t_j^b| + \chi_b|x_i - x_j| + \chi_c|t_i^d - t_j^d| \tag{57}$$

A small relatedness value corresponds to a high relatedness. The Shaw remove operator first selects one vessel randomly. Then, a vessel is randomly selected from the removed vessels, and all non-removed vessels are sorted in the non-decreasing order of their relatedness value to the selected vessel. A determinism parameter $U \geq 1$ is used to introduce randomness in the selection of vessels.

Time-related remove operator: This operator firstly chooses the vessel with the maximum cost into V_r. Similar to the Shaw remove operator, this operator calculates the relatedness with respect to the berth starting and ending time of the non-removed vessels and the selected vessel. For example, vessel *i* is selected first, and then the non-removed vessels are sorted in decreasing order according to the number of overlapped time periods occupied by vessel *i*. Only the non-removed vessels showing overlapped time periods with vessel *i* will be removed. If the number of removed vessels is less than λ^p, the most costly vessel among all the non-removed vessels will be selected. This procedure will be repeated until λ^p vessels are removed.

Berth-related remove operator: Different from the time-related remove operator, the berth-related remove operator calculates the relatedness with respect to the desired berthing position of the selected vessel and the non-removed vessels at the same terminal. Moreover, if a non-removed vessel and the selected vessel occupy the same time periods, the non-removed vessel will be removed immediately; otherwise, the operator decides whether to remove the vessel randomly.

4.2 Repair operators

Next, we introduce the repair operators used in the algorithm. Given a partial solution s_a and a set of removed vessels, the repair operators aim at inserting removed vessels back into s_a. Let V_a be the set of inserted vessels. A good candidate berthing time and berthing position for a vessel to be inserted can be found according to the following proposition.

Proposition 4.1 *Given a vessel $i \in V_a$ to be inserted and a set of inserted vessels $j \in V_s$, there is an optimal berth plan in which vessel i to be inserted moors at its expected arrival time or at the time immediately after another vessel's departure or departure at another vessel's berthing time ($t_i^b = ETA_i$ or $t_j^d = t_i^b$ or $t_i^d = t_j^b$) and moors at its desired position or at the position to the immediate right and left of another vessel for some j ($x_i = b_i^p$ or $x_i = x_j - l_i$ or $x_i = x_j + l_j$).*

Proof Without consideration of speed-up time of each vessel, Hu et al. (2014) showed that a good berthing time and berthing position of vessel *i* can be chosen from following set of candidate points on the space-time diagram: desired position and arrival time $\{(b_i^p, ETA_i)\}$, left and right side of other inserted vessels and arrival time $\{(x_j + l_j,\ ETA_i)$, $(x_j - l_i,\ ETA_i)\}$, desired position and departure time of other inserted vessels $\{(b_i^p,\ t_j^d)\}$, left and right side of other inserted vessels and departure time $\{(x_j + l_j,\ t_j^d)$, $(x_j - l_i,\ t_j^d)\}$. By replacing the objective function in the properties 1–3 in Kim and Moon (2003), we can obtain two additional sets of candidate points on the space-time diagram: desired position and starting time $\{(b_i^p, t_i^d = t_j^b)\}$, left and right side of other inserted vessels and arrival time $\{(x_j + l_j, t_i^d = t_j^b)$, $(x_j - l_i, t_i^d = t_j^b)\}$. □

According to Proposition 4.1, the optimal berthing time and berthing position can be found from six sets of candidate points on the space-time diagram. Instead of inserting each vessel to its best position, in this study, we reinsert vessels according to two priority rules: time priority and cost priority.

Time priority: Although fewer position deviations of vessels would result in less QC-hours demand, berthing at a better position may result in more departure delay time and penalty cost. Therefore, in this rule, we insert the vessels as early as possible and assign priorities to candidate assignments according to the rule that an assignment with good berthing time is prior to the one with a good berthing position. Therefore, the set of candidate assignments of vessel $i, i \in V_r$ can be ranked based on the ascending order of deviation from its desired position first and then based on the ascending order of time-related cost including the penalty cost and speed up cost based on the shortest berthing periods.

Cost priority: Similar to the *time priority* rule, a set of candidate berth plans for vessel $i, i \in V_r$ can be obtained when QC-hours demand is not considered. Different from the *time priority* rule, we apply the priority to candidate assignments considering both berthing position and time. Let B_i^p be the set of the candidate berth plans for vessel *i* at terminal *p*. Given a position deviation $\mu_{i,k}$ of vessel *i* with candidate assignment $k, k \in B_i^p$, we can obtain the shortest time duration of vessel *i* berthing, $\frac{(1+\beta\mu_{i,k})QC_i}{(r_i^{max})^\alpha}$. Then, the estimated additional cost of a candidate assignment can be obtained using Eq. (27). In this rule, the candidate assignments are ranked according to the non-decreasing order of their estimated additional cost. This rule aims to choose better berthing positions for removed vessels when departure delay and speed-up do not occur and identify a better berthing time when departure delay and speed-up occur.

After assigning the candidate berthing time and position to a vessel, the departure time and detailed QC assignment need to be made. A parameter *H* between (0.2, 0.5) is used to determine the time duration of berthing. In this study, two methods are employed to assign a QC profile to each vessel with a given berthing time, berthing position and service time. The first method assigns the maximum number of QCs to the vessel at each time period of its service. Let QC_{it}^{need} be the number of QCs needed by vessel *i* at time *t*, which can be calculated as follows:

$$QC_{it}^{need} = max(r_i^{min}, \lceil (Task_{it}^u - (r_i^{min})^\alpha T_i^r)(1/\alpha) \rceil) \tag{58}$$

wherein $Task_{it}^{u}$ is the unsatisfied QC-hour demand of vessel i at time t, and T_i^r is the remained service time of vessel i. Then, the number of QCs assigned to vessel i at time t is equal to the minimum value of QC_{it}^{need} and the number of available QCs at time t. The smarter greedy insertion proposed by Iris et al. (2017) is adapted as the second method to develop detailed QCs assignment. Four repair operators can be obtained by combining the above rules and QC assignment methods. The procedure of repair operators is shown in Algorithm 2.

5 Numerical experiments

In the numerical experiments, we consider three terminals in a port. Two case studies consisting of comprehensive numerical experiments are conducted to test the proposed ALNS algorithm under different settings. In each case study, we investigate three scenarios with different numbers of arriving vessels, and each scenario includes ten instances. The planning horizon is set as 168 working hours (one week) in both cases. The interference coefficient α is set as 0.9, and the increase in the QC-hours needed due to berthing deviation β is 0.01. The details of cost parameters $(c_i^1, c_i^2, c_i^2, c^4)$ can be refereed to Meisel and Bierwirth (2009). The handling rate of the quay crane h^{load} is assumed to be 30 TEUs per hour. All the costs in the following section are in thousands of dollars.

Case study I includes 30 benchmark instances from Meisel and Bierwirth (2009). The length of each quay is 1000 ms, and 10 QCs are available at each terminal. The water depth restriction is not considered in this case. Case study II consists of 30 randomly generated instances based on the empirical data in Meisel and Bierwirth (2009), which are more complex. Three terminals vary in the length of the quayside, the number of quay cranes, and the water depth. The draft of each vessel is generated based on its length. The characteristics of each terminal and the transshipment cost per thousand TEUs between any two terminals are shown in Table 3. The numerical experiments are conducted using Matlab R2016a on a laptop with Windows 7 operating system, Intel Core i7 2.20GHz CPU and 32GB RAM. Running time is reported in seconds.

The parameters of the ALNS are tuned by using three different instances chosen randomly for each scenario of the first set of instances. In this phase, 11 parameters are tuned: the upper number of vessels to remove, three parameters in Shaw removal, three parameters in controlling the simulated annealing framework, and four parameters in the weigh-adjustment of operators. The tuning method used in Iris et al. (2017) is employed to tune the parameters. First, two reasonable values for each parameter are proposed, and then all combinations of these parameters are analysed. The initial parameter values for ALNS are decided in this phase. In the second phase, each parameter is tested for the other four reasonable values based on the initial parameter setting, while the rest of the parameters remain the

Table 3 General information of each terminal

Terminal	Water depth(m)	Length(m)	Quay cranes	Transshipment cost ($/TEU)		
				1	2	3
1	15	1200	12	0	3	5
2	12	900	9	3	0	4
3	14	1100	11	5	4	0

same as initial parameter values. The complete tuning phase results in a parameter vector: $\{\lambda_u, \sigma_1, \sigma_2, \sigma_3, \tau, \delta, \xi_1, \xi_2, \chi_a, \chi_b, \chi_c\} = \{0.15, 40, 10, 7, 0.6, 3000, 0.05, 0.0001, 3, 0.01, 0.5\}$. The maximum iteration is set as 100000, and the cooling rate is set as 0.9996.

5.1 Case study I - Homogeneous terminals with instances in Meisel and Bierwirth (2009)

Case study I aims to analyse the performance of the proposed heuristic algorithm and compare the total costs with and without consideration of cooperation using different instances in Meisel and Bierwirth (2009). All the terminals have the same length of quay and available QCs, and all vessels can be diverted to any terminal without water depth restriction. In this case study, three scenarios are investigated: Scenario I (idle status) considers 20 arriving vessels at each terminal; Scenario II (mixed status) considers different numbers of vessels, 20, 30 and 40, at the three terminals, respectively; and Scenario III (busy status) considers 40 vessels at each terminal.

The C-BAQCAP model is solved with a 0.5% relative optimality and 5 h upper limit of computational time by the commercial solver, Gurobi, called by Yalmip. Gurobi has been identified with the best performance on MILP problems compared to various existing commercial solvers (Mittelmann, 2023). The ALNS algorithm is applied to each instance for ten times. The best objective value in each instance is reported in Table 4. C-BAQCAP and BAQCAP represent the problems with and without cooperation, respectively. G0 is the optimality gap of Gurobi, which is calculated between the upper and lower bounds. G1 is the gap between the best solutions generated by ALNS and Gurobi, and the positive number means that Gurobi generates better solutions. The column “No” specifies the instances numbers in Iris et al. (2017). For example, [1, 3, 10] in the first instance of Scenario 1 represents the combination of instances 1, 3 and 10. “—” represents that the solver cannot find a feasible solution within the given time limitation. G2 reflects the percentage of total cost that can be saved under cooperation in each instance.

We first compare the computational performance between Gurobi and the proposed ALNS algorithm. It can be seen from Table 4 that Gurobi is much more time-consuming in solving all the instances compared to the proposed ALNS algorithm, and it can achieve optimal solutions within a computational time of 5 h only for 10 instances in Scenario 1 (small size, 60 vessels). The optimal global solutions are found in 9 out of 10 instances (the gaps between the upper and lower bounds are less than 0.5%). For all of the instances in Scenario 2 (medium size, 90 vessels) and Scenario 3 (large size, 120 Vessels), no optimal solutions can be found within 5 h. The performance of Gurobi becomes worse when the instance size increases. Conversely, the proposed solution algorithm is much more efficient than Gurobi. All instances in the three scenarios can be solved within the computational time of around 4 min. The solutions in Scenario I generated by Gurobi are better than those of ALNS, but the average gap is quite small, ranging between 0.7% and 5.2%. Such a small gap makes the quality of solutions obtained by ALNS acceptable in practice, especially considering the computational efficiency for large-scale problems.

Then, we compare the total costs with and without consideration of cooperation. The total costs under C-BAQCAP (with cooperation) are the best results obtained by ALNS and Gurobi, and those values under BAQCAP (without cooperation) are the best upper bounds obtained from Iris et al. (2017). In Scenario 1, all the terminals are relatively idle (only 20

Table 4 Comparison of solution methods under different scenarios

		No	C-BAQCAP						BAQCAP	G2(%)
			ALNS		Gurobi			G1(%)		
			Obj	Time(s)	Obj	G0(%)	Time(s)			
Scenario 1	1	[1,3,10]	227.7	82.5	216.4	6.95	18009	5.2	249.7	13.3
	2	[1,5,6]	193.6	67.0	188.6	0.46	9958	2.2	198.5	4.5
	3	[3,8,10]	190.9	73.1	183.9	0.44	2658	3.8	221.7	17.1
	4	[1,7,10]	206.4	73.5	200.0	0.48	646	3.1	241.4	17.2
	5	[1,2,3]	198.5	74.0	192.0	0.47	1156	3.4	214.3	10.4
	6	[3,7,9]	196.7	72.4	190.9	0.47	2112	3.1	219.4	13.3
	7	[2,6,10]	176.3	62.6	175.0	0.26	408	0.7	200.8	12.9
	8	[5,6,9]	179.8	63.6	176.6	0.43	736	1.8	189.5	6.8
	9	[4,7,9]	189.5	68.6	184.3	0.43	715	2.8	219.3	16.0
	10	[7,8,9]	184.8	66.2	177.2	0.43	390	4.3	199.2	11.1
Scenario 2	1	[1,12,29]	319.0	131.0	–	–	18000	–	372.9	14.5
	2	[7,11,29]	322.7	137.7	–	–	18000	–	414.8	22.2
	3	[5,20,26]	316.0	120.9	–	–	18000	–	417.6	24.3
	4	[8,16,26]	302.0	115.0	–	–	18000	–	399.2	24.3
	5	[2,19,28]	334.9	125.5	–	–	18000	–	480.0	30.2
	6	[4,17,24]	359.7	120.3	–	–	18000	–	461.3	22.0
	7	[8,12,22]	276.1	109.9	–	–	18000	–	308.8	10.6
	8	[7,16,21]	299.5	122.7	–	–	18000	–	383.7	21.9
	9	[3,17,30]	304.6	131.3	–	–	18000	–	364.0	16.3
	10	[8,16,21]	283.9	133.1	–	–	18000	–	371.8	23.6
Scenario 3	1	[25,28,29]	443.1	210.2	–	–	18000	–	616.0	28.1
	2	[24,26,28]	545.2	216.5	–	–	18000	–	772.7	29.4
	3	[21,25,29]	416.1	201.0	–	–	18000	–	557.0	25.3
	4	[23,26,28]	606.2	252.3	–	–	18000	–	724.4	16.3
	5	[24,26,29]	540.8	256.7	–	–	18000	–	718.8	24.8
	6	[21,25,26]	442.4	235.7	–	–	18000	–	579.3	23.6
	7	[21,23,24]	653.7	255.9	–	–	18000	–	718.6	9.0
	8	[22,24,28]	515.8	245.4	–	–	18000	–	714.3	27.8
	9	[21,24,29]	578.9	237.1	–	–	18000	–	691.4	16.3
	10	[21,22,28]	491.8	221.9	–	–	18000	–	633.7	22.4

arriving vessels). In most instances, more than 10% cost can be saved under cooperation, and only two instances (Instances 2 and 8) get cost savings less than 7%. Scenario 2 with different numbers of vessels at different terminals shows a significant reduction in the total cost. Most of the instances have cost savings between 22% and 30% (Instance 5), and only three instances have less than 20% but more than 10% of cost savings. A significant cost reduction can also be observed in Scenario 3, where each terminal is busy with 40 vessels. Among the ten instances in Scenario 3, only one instance (Instance 7) shows less than 10% cost savings, and the highest cost savings occur in Instance 1 (cost reduced by 29%). In general, the cost saving in all instances under cooperation ranges from 5% to 30%, which proves that the terminal operators can significantly benefit from cooperative operation.

5.2 Case study II - Heterogeneous terminals with randomly generated instances

Case study II aims to compare the berthing plans with and without cooperation based on randomly generated instances. Compared to Case study I, more complex and practical considerations are included in Case study II, where three terminals vary in the length of the quay, the number of quay cranes, and the water depth. The restriction of water depth is taken into account as well.

The majority of literature studies on BAQCAP have investigated the optimal operation of a single terminal. In order to investigate the cooperation among different terminals, Case study II generates instances to accept heterogeneous characteristics of terminals and vessels, such as water depth, the draft of vessels, and so on. The length of quays and the number of quay cranes are various to reflect the difference between terminals. The number of arrival vessels at each terminal in different states is adjusted based on the quay's length. For instance, the length of terminal 1 is 1200 ms, as shown in Table 3. Therefore, the number of arrival vessels at terminal 1 is set to 24, 36, and 48 when terminal 1 is in the idle, normal, and busy state, respectively. In Case study I, the performance of the proposed ALNS algorithm has been analysed. Case study II aims to evaluate the improvement of the service level under cooperation based on multiple criteria. The number of delayed vessels (DV), the number of speed-up vessels (SV), the number of penalized vessels (PV), the total delayed time (DT) in hours, and the total cost (TC) are reported for each instance with and without consideration of cooperation, as shown in Table 5. PV represents the vessels whose departure time exceeds the latest departure time. Moreover, the average values (bold font) in each scenario are also given. The Gap (in percentage) reflects the reduction of total cost under cooperation compared to that without cooperation.

In Scenario 1, the number of arrival vessels at each terminal is 24, 18, and 22, respectively, and all terminals are relatively idle. It can be observed that compared to the instances without cooperation, the total cost reduction under cooperation ranges from 6.8% (Instance 10) to 22.7% (Instance 4), with a maximum reduction of 59.1 ($\times 10^3$ \$). It is noticeable that the number of delayed vessels (DV) and total delayed time (DT) drop by 11.1 vessels and 27.4 h on average, and no vessels depart later than their latest departure time. Moreover, the number of speed-up vessels (SV) decreases as well, which would reduce the fuel consumption caused by vessel acceleration. A more significant reduction in the number of delayed vessels (DV) and total delay time (DT) can be observed in Scenario 2, where the three terminals are in a mixed state (idle, normal, busy). The total delay time (DT) is reduced by a maximum of 225 h (Instance 5), and the number of delayed vessels (DV) decreases by a maximum of 28 (Instance 6). The total cost (TC) is reduced by a maximum of 51.5% with a reduction of 401.2 ($\times 10^3$ \$). In the meanwhile, the amounts of penalized vessels (PV) and speed-up vessels (SV) drop significantly as well, which are reduced by 8.6 and 9.1 vessels, respectively. In Scenario 3, each terminal is in a busy state with 48, 36, and 44 arriving vessels, respectively. When cooperation is considered, the number of delayed vessels (DV) and the total delay time (DT) are averagely reduced by 17.5 vessels and 119.8 h, respectively. The total cost (TC) can be reduced by 42.4% at most. The number of speed-up vessels (SV) is reduced most in Scenario 3, which reaches 11.5 vessels on average.

Compared to other scenarios, the advantages and benefits under cooperation in Scenario 2 are the most significant, where the total cost reduced in each scenario is 14.9%, 41.6%, and 30.6% on average. This happens because the states of terminals in Scenario 2 are various, and thus, there are more opportunities to divert vessels to other terminals. Above all, the numerical results show that cooperation among multiple terminals can significantly reduce the number of delayed vessels, the total delay time, and the total operation cost, which are 16.9 vessels, 96.8 h, and 32.8% on average, respectively. Moreover, almost no vessels would depart later than their latest departure time, and fewer vessels would speed up to reach their berthing time. It indicates that the coordinated operation among multiple terminals in a port would maximise productivity based on existing resources and significantly improve each terminal's level of service.

Then, we show the range of delay time in each scenario in Table 6. It can be observed that most vessels' delay time ranges from 1 to 4 h no matter considering cooperation or not. Compared to the results without cooperation, the number of vessels with delay time exceeding 4 h is reduced significantly under cooperation, reduced by 212 vessels in three scenarios. Only 23 vessels show delay time greater than 4 h under cooperation, while the number without cooperation is 235. Moreover, there are 92 vessels with a delay time greater than 8 h when cooperation is not considered, and the number is reduced to 4 under cooperation. The results further prove that cooperation can effectively reduce vessels' delay time and shorten vessels' staying time at terminals.

The average percentages of diverted vessels, transshipped containers and cost savings in each scenario are further shown in Fig. 3. It can be observed that an increasing number of vessels are diverted to non-scheduled terminals as the total number of arrival vessels increases and the status of terminals changes from idle to busy. On the one hand, only a few vessels can not depart before the latest departure time when terminals are in the status of idle. In contrast, the status of busy on each terminal would lead to a significant number of delayed vessels. On the other hand, diverting a few vessels to non-scheduled terminals can make delayed vessels better berth plans when terminals are relatively idle. More vessels need to be diverted to release related resources for rescheduling vessels when terminals are relatively busy. It is noticeable that although Scenario 3 has the highest proportion of transshipped containers and diverted vessels, its cost savings are less than Scenario 2. This is because each terminal's status in Scenario 2 is various, and coordination can effectively utilise the idle resources of terminals. In Scenario 3, each terminal is in busy status, and the berthing vessels are regrouped and assigned to each terminal to maximise the utilisation of resources in terminals. It indicates that cooperation is most significant in the situation where there exists a certain difference in each terminal's resource utilisation.

As shown in Fig. 3, the percentage of transshipped containers ranges from around 15% to 28%. Nearly one-third of arrival vessels have changed berthing terminals. To reveal whether cost savings mainly come from transshipment, sensitivity analysis is conducted by varying the transshipment cost. The first instance in each scenario is taken as an example. The transshipment cost is measured in thousands of dollars per thousand TEUs, and the transshipment cost between any two terminals is identical. The corresponding sensitivity analysis results are shown in Fig. 4.

Firstly, when the transshipment cost is not considered, the cost savings are 94.4, 234.0, and 336.6 ($\times 10^3$\$), respectively, which corresponds to 34.0%, 42.0%, 37.8% of cost reduction. It reflects that coordinated operation among terminals can achieve more than 34% cost savings in any scenario by reassigning arriving vessels to the corresponding terminals. Secondly, the proportion of diverted vessels and transshipped containers and cost savings decrease as the transshipment cost increases. As the transshipment increases, diverting ves-

Table 5 Comparison of performances with and without cooperation

		With cooperation					Without cooperation					Gap(%)
		DV	DT	PV	SV	TC	DV	DT	PV	SV	TC	
Scenario 1	1	6	9	0	0	225.5	19	44	0	3	277.0	18.6
	2	9	13	0	0	202.1	16	28	0	2	220.0	8.1
	3	13	19	0	2	240.1	21	53	2	1	274.8	12.6
	4	6	6	0	0	201.1	22	45	0	1	260.2	22.7
	5	5	8	0	1	220.6	20	37	0	1	253.0	12.8
	6	3	4	0	0	195.5	15	31	0	3	248.4	21.3
	7	8	8	0	0	208.1	18	29	0	0	224.7	7.4
	8	8	12	0	0	223.1	20	47	1	3	277.1	19.5
	9	9	12	0	0	214.4	18	35	1	3	252.3	15.0
	10	7	7	0	0	197.5	16	23	0	0	212.0	6.8
	Aver	**7.4**	**9.8**	**0**	**0.3**	**212.8**	**18.5**	**37.2**	**0.4**	**1.7**	**250.0**	**14.9**
Scenario 2	1	23	35	0	4	396.2	44	106	4	11	558.0	29.0
	2	28	41	0	1	401.4	38	102	2	8	528.8	24.1
	3	33	51	0	3	469.9	58	272	17	9	867.4	45.8
	4	25	37	0	3	420.9	49	197	10	10	773.8	45.6
	5	35	76	3	5	560.7	54	301	15	10	1041.6	46.2
	6	23	45	0	0	427.8	51	244	11	12	856.0	50.0
	7	15	18	0	0	378.6	42	196	8	16	779.8	51.5
	8	29	42	0	4	406.6	50	153	11	10	648.4	37.3
	9	21	27	0	0	372.5	46	135	7	12	615.1	39.4
	10	24	29	0	2	396.0	44	126	4	15	573.9	31.0
	Aver	**25.6**	**40.1**	**0.3**	**2.2**	**423.1**	**47.6**	**183.2**	**8.9**	**11.3**	**724.3**	**41.6**

Table 5 (continued)

		With cooperation					Without cooperation					Gap(%)
		DV	DT	PV	SV	TC	DV	DT	PV	SV	TC	
Scenario 3	1	36	86	2	11	659.2	57	192	7	21	889.0	25.9
	2	49	79	0	10	639.9	72	288	17	15	1054.0	39.3
	3	43	73	1	8	593.3	61	181	10	16	806.3	26.4
	4	43	74	0	6	577.4	64	244	15	18	1002.5	42.4
	5	40	80	1	7	657.2	57	183	6	22	890.5	26.2
	6	44	64	0	6	533.9	54	147	5	17	733.8	27.2
	7	40	68	0	7	584.9	58	155	6	17	777.7	24.8
	8	41	60	1	9	577.6	57	148	8	23	775.8	25.5
	9	47	81	0	7	589.8	61	214	10	21	936.9	37.0
	10	48	92	1	5	654.8	65	203	7	21	872.9	25.0
	Aver	**43.1**	**75.7**	**0.6**	**7.6**	**606.8**	**60.6**	**195.5**	**9.1**	**19.1**	**873.9**	**30.6**

Table 6 Comparison of delay time with and without cooperation

Time range (hour)		[1,4]	(4,8]	(8,12]	(12,16]	(16,~]
Without cooperation	Scenario 1	172	11	2	0	0
	Scenario 2	370	59	21	11	15
	Scenario 3	490	73	22	12	9
With cooperation	Scenario 1	73	1	0	0	0
	Scenario 2	249	6	0	1	0
	Scenario 3	416	12	2	1	0

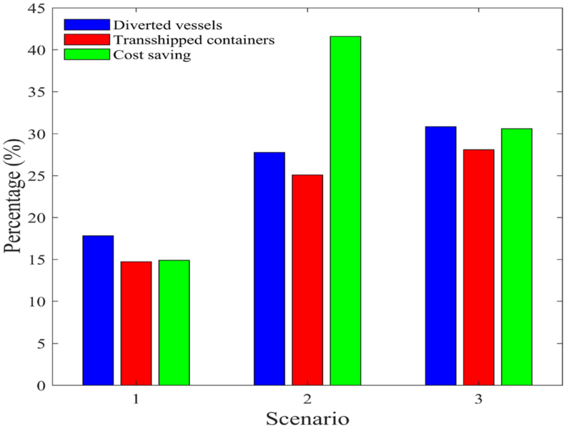


Fig. 3 The percentages of diverted vessels, transshipped containers and cost saving

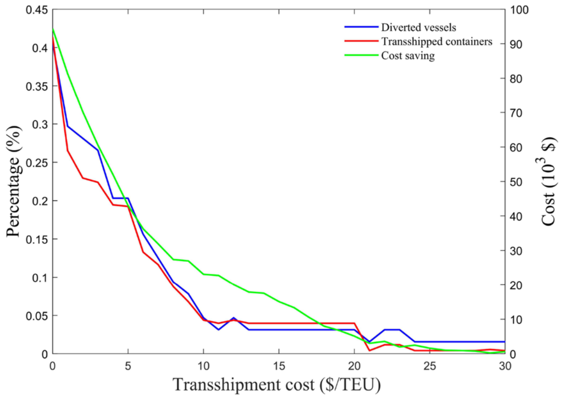
sels to non-scheduled terminals can obtain better berthing plans, but it would increase the total transshipment cost, which might no longer be economical. Especially in Scenario 1, the cost savings and transshipped containers are near zero when the transshipment cost exceeds 25 ($\times 10^3$ \$) per thousand TEUs. Thirdly, when the transshipment ratio is around 5% and 10%, the corresponding cost savings in the three scenarios are 23.1 and 27.4, 47.6 and 100.7, 59.1 and 118.8 ($\times 10^3$ \$), respectively. Meanwhile, the corresponding transshipment costs are 10 and 8, 20 and 10, 26 and 15 (\$/TEU), respectively. If the transshipment cost in Scenario 3 decreases to 5 (\$/TEU), 161.8 ($\times 10^3$ \$) can be saved with only 4.7% transshipped containers. It indicates that cooperation can also achieve significant cost savings with only a few transshipped containers.

5.3 Managerial implications

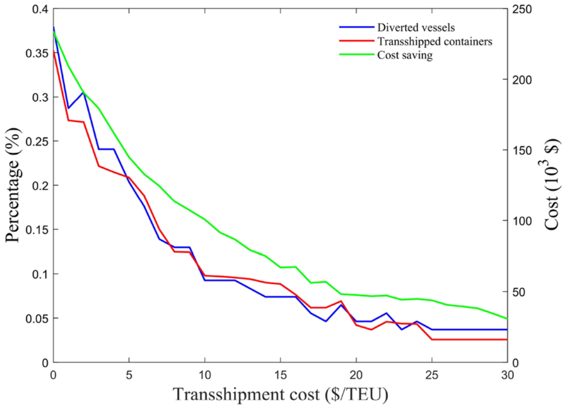
This paper investigated the coordinated operation among terminal operators in a port to support the decision-making on berth allocation and quay crane assignment. The numerical results verify the benefits of cooperation to reduce relevant costs and improve the level of service, and the research findings provide several managerial implications for the cooperative operation of multiple terminals in a port as follows.

Firstly, terminal operators should give attention to seeking cooperation by exchanging partial vessels when terminals are in relatively busy status. The results show that even just a small portion of diverted vessels and containers can significantly reduce the delay time. Exchanging vessels among terminals may reduce the profits from handling containers but

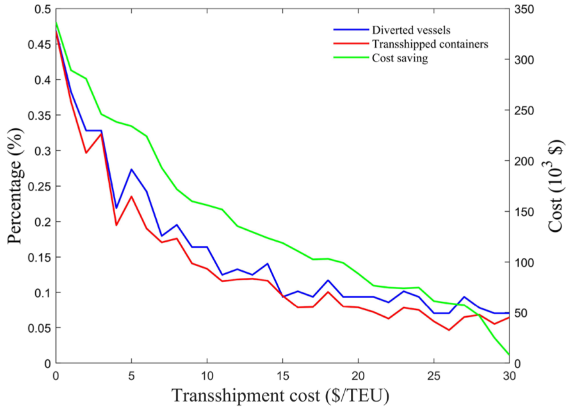
Fig. 4 Sensitivity analysis on transshipment cost



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

considerable benefits could be generated such as the improvement in service level. Based on the optimal berth allocation and quay crane assignment plan under cooperation, terminal operators could make decisions on which vessels should be diverted in/out, and further transport export containers that need to be loaded to the desired yard area in advance, which could help to reduce extra handling time and costs caused by deviation from the desired berths of diverted vessels.

Secondly, terminal operators should consider the negative effect of containers transshipped between terminals on the port operation when cooperation occurs. The results show that cooperation may not be economical anymore when the transshipment cost of containers between terminals rises to a certain degree. The transshipment cost can be not only the economic cost of transshipment but also the negative impact caused by transshipment, such as the reduction of traffic efficiency in the yard and port. Terminal operators could measure the perceived transshipment cost considering multiple negative impacts of exchanging vessels to make decisions on whether to participate in cooperation and the quantity of exchanged vessels.

Thirdly, port authorities need to adopt appropriate policies to guide cooperation among terminals in a port. The results indicate that cooperation among terminals can achieve significant cost reduction and service level improvement. Cooperation can make better utilisation of resources in the port and provide better services to attract more vessel calls. However, proper policies are needed to ensure stable and smooth cooperation. The generated berth allocation and quay crane assignment plan by the proposed method can be used to evaluate the cooperation stability with the aid of game theory. With iterative generating and evaluating solutions, terminal operators could obtain an integrated berth allocation and quay crane assignment solution under stable cooperation.

6 Conclusion

In this paper, the BAQCAP was investigated by allowing cooperation among multiple terminals in a port named C-BAQCAP. An integer linear programming model was developed to formulate the C-BAQCAP with consideration of multiple practical constraints like various water depths, container transshipment costs, and quay crane interference. An ALNS algorithm consisting of four destroy operators and four repair operators were proposed to efficiently solve the model. To evaluate the proposed solution algorithm, comprehensive numerical experiments were conducted in two case studies: one considers homogeneous terminals with instances from literature, and the other includes heterogeneous terminals with randomly generated instances. The numerical results indicated that the proposed ALNS algorithm outperformed the commercial solver Gurobi on both computational time and convergence, especially in large-scale instances. Moreover, the results showed that cooperation among multiple terminals in a port could significantly reduce the number of delayed vessels and total delay time of vessels, which leads to a higher level of service.

Key observations from the case studies are outlined as follows, including the benefits of cooperation and relevant impact factors:

(1) The advantages and benefits of cooperation are significant. Under the cooperation, the penalty cost caused by vessels' delay can be reduced, and the staying time at terminals

and the speed-up time for catching the berthing time can be shortened, which further reduces vessels' emissions. In addition, the range of delay time is greatly reduced, and almost all the vessels' delay time is less than 4 h, while there are 92 vessels with delay time greater than 8 h when cooperation is not considered;

(2) The benefit of cooperation varies under different scenarios. The benefit is marginal when each terminal is relatively idle (limited calls at each terminal), and the benefit becomes more significant when the terminals are in a busier status;

(3) The benefit of cooperation is restricted by the transhipment cost of containers between terminals. Relevant profits decrease as the unit transhipment cost increases, and considerable profits can be obtained by transferring a small portion (around 5%) of containers.

The future work will focus on the following aspects. First, it is essential to design appropriate mechanisms and regulations to guide the cooperation among terminal operators, such as container transferring profit and cost (Hu et al., 2020). The second is to consider the operations of other resources in container terminals. Although both berth allocation and quay crane assignment are considered in this study, the storage yard and container trucks' operations are out of consideration. In reality, container trucks deliver containers between the yard and quayside, and yard cranes operate the containers in the yard, which are important parts of terminal operation. Therefore, an integrated terminal operation plan, including berth allocation, QC assignment, yard crane assignment, and so on, is worthy of investigation. The last is to consider the uncertainties and unexpected events in real life, such as stochastic arrival time of vessels and disruptions of quay cranes.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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