Berth allocation and quay crane-yard truck assignment considering carbon emissions in port area

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Abstract: As environmental issues become increasingly prominent, the green port has been the focus of marine industry to sustain the development of global economy. Carbon emissions of port area mainly come from water area and land area of port. The effective resource allocation and equipment assignment can not only reduce the carbon emissions, but also improve the service efficiency. Thus, this paper considers the berth-quay crane-yard truck allocation problem (B-QC-YTAP) and formulates it as a multi-objective model, where the objectives are to minimise the total carbon emissions in port area, and minimise the average waiting time in port and departure delay for each vessel. To solve the proposed model as well as obtain the Pareto optimal solutions, the non-dominated sorting genetic algorithm II (NSGA-II) is also introduced. Finally, a numerical experiment is conducted to test the effectiveness of model and algorithm, followed by the trade-off analysis between the two objectives.

Keywords: B-QC-YTAP; carbon emissions; service efficiency; NSGA-II; multi-objective.

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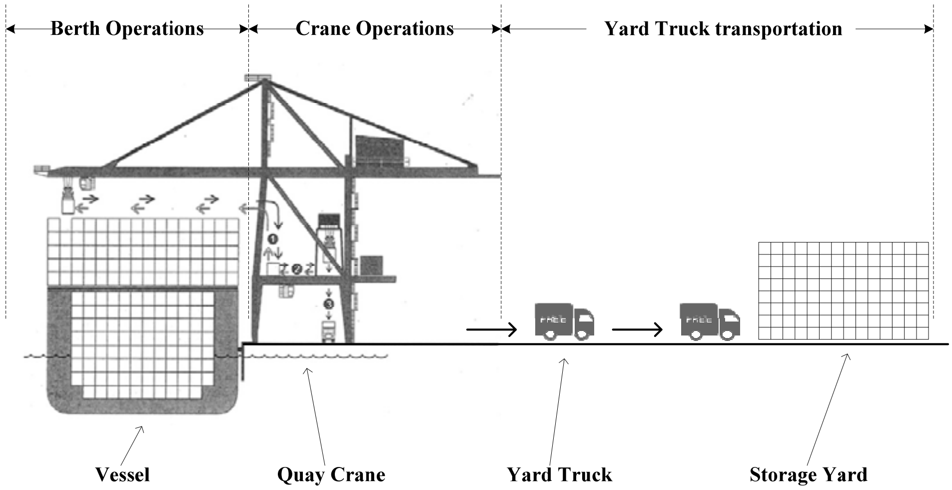
1 Introduction

With the accelerating process of global economic integration, the international trade gets a dramatic growth, among which the shipping has become the main transportation mode with its advantages of low cost and large volume of transport. It is reported that the world seaborne trade volumes have exceeded 10 billion tons, accounting for over 80%of total world merchandise trade in 2015 (UNCTAD, 2016). However at the same time, the shipping industry's energy consumption and greenhouse gas emissions are increasing year by year. As reported by International Maritime Organisation (IMO), the marine industry contributes an average 1.015 billion tons carbon dioxide (CO_2), accounting for about 3.1% of the total global carbon emissions every year; and it is predicted that 1.4 billion CO_2 will be produced by shipping in 2020 which accounts for 6% of the total global carbon emissions; if no measures are taken, the shipping emissions of greenhouse gases in 2050 will increase 87%–160% than that in 2020 and it will be up to 18% of global CO_2 (IMO, 2015). Although the total CO_2 discharged by shipping industry is relatively low, the growth rate of energy consumption and carbon emissions cannot be ignored. Since energy consumption and carbon emissions are increasingly attracting extensive attention of the whole society with the worsening of the global climate, the marine industry should take the responsibility to participate in the global carbon emissions reduction plan and make a contribution to the sustainable development of human beings.

Port area includes port land area and port water area. Carbon emission of port water area mainly comes from the anchored ships. On the one hand, the ship will discharge massive carbon emissions in the process of navigation, especially near port area; on the other hand, large amount of CO_2 will be produced by the vessel during the berthing process until its departure. A study shows that carbon emission from anchored ships account for about 30% to 50% of the total carbon emission of the port area (Ma et al., 2014). The carbon emission of port land area mostly comes from inland transportation system, mainly including loading and unloading equipment such as quay cranes (QCs), yard trucks (YTs) and so on, which will produce a large amount of carbon emissions in the process of service for ship. The process of main operations in port area can be depicted as Figure 1. Carbon emissions will markedly influence the air quality of port area and the public health, thus how to allocate port resource so as to reduce carbon emissions of port area and construct green port with low carbon is becoming a global consensus for many important ports.

Figure 1 Process of main operations in port area



Accordingly, the port operators can set out to reduce the carbon emissions of port area from the following two aspects. Firstly, in port water area, carbon emission of vessel is mainly caused by its fuel consumption. The related studies show that the vessel's fuel consumption is concerned with the sailing speed during the voyage, thus the vessel speed should be limit to the optimal one so as to reduce the carbon emission as well as energy consumption in the sailing process near port. And to control the vessel's speed near port, it calls for coordination between the port and the shipping lines to make optimal berth plan (Du et al., 2011). While once the ship enters the anchorage waiting for berthing service, the main engines of vessel will turn off until the vessel departs from the port. However, the auxiliary engines are still running to ensure the daily life of crew, which will discharge CO_2. Thus to reduce the carbon emission in this period, shore power technology is applied, in which the port provides power for the anchored vessel instead its fuel consumption. Yet there exist two difficulties to implement the shore power technology: on the one hand, the infrastructure needs large investment to reform so as to adapt the technology requirement; on the other hand, the lack of the unified fee standards when port provides power to vessel leads to a low motivation to introduce and apply the shore power technology. For these ports without applying shore power technology, the only way to reduce the carbon emission during this period is to reduce the vessel's dwell time in port, which can be achieved by improving the efficiency of port services. Secondly, in port land area, carbon emissions from port equipment can be reduced by resource optimisation allocation, that is to say the integrated berth allocation and quay cranes-yard trucks assignment can improve the service efficiency, which further reduce the carbon emission of service equipment. Meanwhile, it can also reduce ship's berthing time, and then reduce carbon emission from vessel in port water area.

Hence the goal of this paper is to reduce the total carbon emissions in port area by optimising the resource allocation including berth, QC and YT. Additionally, service quality provided by port to vessels must not be reduced, which is another objective of this paper. Therefore, this study intends to construct a multi-objective nonlinear mixed-integer programming (MNMIP) model to solve the berth allocation and quay crane-yard truck assignment problem (B-QC-YTAP). Vessel emissions are calculated by introducing carbon emission factors, and service quality is reflected by the average waiting time in port and departure delay for each vessel. And the shorter the average waiting time and departure delay, the higher the port service efficiency. The MNMIP model is settled by the non-dominated sorting genetic algorithm II (NSGA-II), and finally the trade-off between carbon emission and service efficiency is analysed.

The remainder of this paper is organised as follows. Section 2 is a review of previous research. Section 3 elaborates the B-QC-YTAP considering carbon emissions in port area. The MNMIP model is developed in Section 4 to settle the proposed issue. Thereafter, solution algorithm is proposed in Section 5, in which the NSGA-II is introduced to solve the model. A numerical example is generated in Section 6 to evaluate the proposed model and the trade-off between the two objectives is analysed. Finally, Section 7 concludes the study and provides recommendations for future work.

2 Literature review

2.1 Studies on berth, quay crane, and yard truck allocation problem

Intensive studies have been attempted in the area of port resource allocation, including berth allocation problem (BAP), quay crane assignment problem (QCAP), and yard truck assignment problem (YTAP). Studies on BAPs have been published since the 1990s. Considering whether the vessel arrivals before the plan execution, the related studies can be divided into static BAP (Li et al., 1998) and dynamic BAP (Imai et al., 2001). Concerned with the situation of berth space on the wharf, the problem includes BAP with discrete berthing space (BAPD) (Brown et al., 1994; Imai et al., 2001, 2003) and BAP with continuous berthing space (BAPC) (Kim and Moon, 2003; Li et al., 1998; Lim, 1998). The detailed review of recent research on BAP is studied by Bierwirth and Meisel (2010).

Meanwhile, the QCAPs have also been widely discussed in the literature. Daganzo (1989) made the first effort on QCAP, and he studied the static and dynamic QC scheduling problem for multiple containerships with the objective of minimising the total delay cost for all vessels. Kim and Park (2004) firstly extended the QCAP by incorporating non-interference constraints of QCs, and they developed a branch and bound method and a heuristic algorithm to solve the proposed mixed integer programming (MIP) formulation. Choo et al. (2010) studied the QCAP where clearance and yard congestion constraints were included, and an MIP model was proposed as well as the solution algorithms to solve the problem in their work. Chung and Chan (2013) proposed a novel genetic algorithm to deal with the QCAP, in which a workload balancing heuristic was adopted to improve the search efficiency. For recent survey on QCAP, please refer to Bierwirth and Meisel (2015).

As for YTAPs, Nishimura et al. (2005) proposed a truck assignment method called ‘dynamic routing’ for solving the YT routing problem at container terminals, which was demonstrated that it was efficient to reduce the trucks travel distance. Ng et al. (2007) addressed the problem of scheduling trucks in container terminal with sequence-dependent processing times and different ready times by formulating an MIP model. Han et al. (2008) integrated YT operations and storage allocation to allocate storage space for containers in transhipment terminal, which can efficiently minimise the traffic congestion caused by YTs. For detailed review of literatures, readers can refer Steenken et al. (2004), Stahlbock and Voß (2008a, 2008b).

2.2 Studies on integrated berth, quay crane, and yard truck allocation problem

Since a vessel's arrival time will affect the berth allocation plan, meanwhile a vessel's time at port largely depends on the numbers of allocated QCs and YTs, and the position of berth can inversely affect the transportation route of YTs, which further affect the port service efficiency, thus the joint scheduling at container terminal is exploding recently.

Park and Kim (2003) studied the berth-quay crane allocation problem (B-QCAP), in which the vessels were supposed in the port at the beginning of the planning horizon. Considering that vessels called at the terminal dynamically over time, Imai et al. (2008) addressed the simultaneous B-QCAP to optimise the vessel's dwell time in port. Meisel and Bierwirth (2009) proposed two meta-heuristics to solve the B-QCAP, in which QC's productivity was taken into account. Kaveshgar and Huynh (2015) developed an MIP model to solve the integrated quay crane and yard truck schedule problem (QC-YTAP) with real-world operational constraints considered, and a genetic algorithm combined with a greedy algorithm was proposed to solve the model. Tang et al. (2014) solved the joint QC-YTAP considering the coordination of QCs and YTs to reduce their idle time between performing two successive tasks, and an improved particle swarm optimisation (PSO) algorithm is then developed to solve this problem. Zhen et al. (2011) studied two tactical level decision problems arising in transhipment hubs, involving allocation for berths, QCs, YTs and the related joint scheduling problems. Related studies on joint resources allocation please see the review work (Bierwirth and Meisel, 2010, 2015).

2.3 Studies on carbon emission in marine industry

Taking energy-saving into consideration, some researchers have made exploration and attempt to reduce emissions of container terminals (Wang and Nguyen, 2017; Mamatok and Jin, 2017; Sampson et al., 2015; Wang et al., 2015a and so on). However, most of the existing literature only considered to reduce the carbon emission produced by vessels. Golias et al. (2009) firstly tried to reduce fuel consumption and vessel emissions by minimising the total waiting time at port, based on the assumption that the shorter the waiting time is, the less the fuel consumption and vessel emissions. The authors regarded the vessel arrival times as a variable to accommodate the objectives and finally provided the ocean carriers with an optimised vessel speed. But they only aim to reduce the emissions produced by vessels in mooring periods, while in fact the emissions for sailing are more prominent, which should not be ignored. Lang and Veenstra (2010) and Alvarez et al. (2010) offset the above deficiency, in which they minimised the fuel consumption for sailing to optimise the berth allocation and speed control problem. Lang and Veenstra (2010) provided a direct quantitative analysis on fuel consumption of vessel and solve the berth allocation and speed control problem with a customised simulation tool. Likewise, they considered the arrival times of vessel as decision variables and integrated this with an optimisation routine to determine the optimal approach speed for arriving vessels. Alvarez et al. (2010) studied a hybrid simulation-optimisation approach on berth allocation to evaluate berthing priority and speed optimisation policies in a marine terminal. They developed a discrete event simulation tool and conducted case study to show the competence of the new berth allocation policy in both fuel savings and terminal productivity. Yet both the two papers mentioned above bypass the nonlinearity between the fuel consumption rate and the sailing speed in different ways. To overcome this difficulty, Du et al. (2011) formulated a tractable mixed-integer second order cone programming (SOCP) model to eliminate the nonlinear complexity involved, and enlightened by the novel and elegant idea of Du et al. (2011), Wang et al. (2013b) proposed two quadratic outer approximation approaches (static and dynamic quadratic outer approximation approach respectively) which can handle general fuel consumption rate functions more efficiently. Hu et al. (2014) added to the analysis of quay-crane allocation and extended the research by Du et al. (2011) and Wang et al. (2013b) to solve the B-QCAP, considering fuel consumption and emissions from vessels. Additionally, the authors provided a direct quantitative analysis of emissions from vessels while moored, which is not addressed in the previous work. What is more, in terms of joint scheduling, Chang et al. (2010) developed a MIP model for B-QCAP considering total energy consumption of all vessels. He (2016) addressed the problem of integrated berth allocation and quay crane assignment for the trade-off between time-saving and energy-saving by formulating an MIP model. In some other perspective, Wanke et al. (2015) developed a nonlinear mathematical model to support the planning of logistic networks considering carbon emission costs resulting from transportation activities. Wen et al. (2017) solved the green route designed issue to improve the ship energy efficiency and reduce the greenhouse gases emissions from ships.

Only a few researchers addressed the carbon emission and energy-saving issues of port equipment in container terminal. In order to reduce emissions from idling truck engines at marine container terminals, Chen et al. (2013) proposed a bi-objective model to minimise both truck waiting times and truck arrival pattern change, and the case study indicated that the truck emissions got significantly reduced by employing truck arrival coordination. To reduce the energy consumption of yard crane, He et al. (2015a) formulated a MIP model to solve the yard crane scheduling problem considering the trade-off between efficiency and energy consumption, and an integrated GA and PSO algorithm was proposed to balance the two objectives. Considering energy consumption, He et al. (2015b) addressed the problem of integrated QCs, internal trucks, and yard crane scheduling, where minimising the total departure delay of all vessels and the total transportation energy consumption of all tasks were the two objectives. For detailed literature about energy-saving at container terminals, please refer to He et al. (2015b). As to detailed source analysis of the carbon emission (including direct emission and indirect emission) in container terminals, Tian and Zhu (2015) adopted a comprehensive assessment method of greenhouse gas emission for Chinese container terminals by utilising the IPCC method and input-output analysis. Yang (2015) applied analytic hierarchy process (AHP) and grey relation analysis (GRA) to determine assess determinants of container terminal operation from a green port perspective. While both their papers focus more on statistical or evaluation analysis, rather than resource optimisation in container terminal.

2.4 Summary, objective and contribution

It is noted that most of the studies on port operations refer to only one resource or equipment, while the whole port area of homework assignments is a closed chain, thus it calls for integrated allocation or assignment to the port resources and equipment including berths, QCs, and YTs. Although some researchers begin to pay attention on the integrated scheduling problem in container terminal, most are about B-QCAP and QC-YTAP, few studies about B-QC-YTAP can be found. On the other hand, the carbon emissions are not comprehensively considered in previous studies, most studies only considered the emissions from vessel while shipping, and others took the emissions of vessel in port into consideration, still some works studied the emissions of port equipment in container terminal, but no studies are found which took all the emission sources in port area into account overall. To overcome these limitations, this work intends to formulate a novel B-QC-YTAP model which considers carbon emissions in port area and service efficiency for port to vessel, and analyses the trade-off between the two objectives.

The above mentioned literature reviews indicate that the integrated B-QC-YTAP considering carbon emissions of port area remains an urgent and crucial issue deserved to be studied. Compared with the pioneering studies, this paper contributes the literature on three folds. Firstly, this paper considers the carbon emissions in port area comprehensively, including carbon emissions in port water area (i.e., carbon emissions from anchored vessels during shipping near port and dwell time in port) and in port land area (i.e., carbon emissions from port equipment such as QCs and YTs). Reducing the CO_2 of the whole port area is significant for reducing the energy consumption as well as improving the port air quality. Secondly, because the service efficiency of port markedly influence the berth allocation plan as well as the shipping and waiting time in port, which further affects the total carbon emissions, thus the effect of QCs and YTs are incorporated to construct a B-QC-YTAP model. Thirdly, a multi-objective function is formulated to reduce the carbon emissions in port area as well as to improve the service efficiency, and the trade-off analysis of the two goals provides insightful suggestions for port operators when determining the resource allocation plan considering port environmental pollution. To the best of our knowledge, studies for the integrated B-QC-YTAP considering emissions reduction of the whole port area have not existed, and the issue is deserved to pay effort to.

3 Problem statement

In B-QC-YTAP, vessels call at the terminal over time, and the terminal operators make berthing decision as well as allocate a certain number of QCs and YTs to each vessel according to the information provided by shipping lines. Once a vessel enters the port area with an R-knots radius, it informs the related information (including the time to enter the port area, vessel speed, the volumes to be loaded or unloaded, and so on) to the port. Accordingly, the port planners decide when and where the vessel is moored and how many QCs and YTs are assigned to it, and then feed a suggested shipping speed back to the vessel so as to improve the service quality and reduce the carbon emissions. To have a more intuitive understanding, Figure 2 illustrates the B-QC-YTAP in two-dimensional plane. The horizontal axis represents the berthing position along the wharf, while the vertical one represents the time step in planning horizon above the horizontal axis and the distance step in storage yard below the horizontal axis. Each rectangle represents a vessel, with the length denoting the vessel length and the height is the handling time. The small boxes in each rectangle stand for the volume of cargoes loading and unloading. When a vessel arrives at the port before its berthing time, it will wait at the anchor point until the berth is available. When vessel to be served, the handing time depends on the amount of assigned QCs and YTs. The QCs transfer the containers from the vessel to the YTs, and then the YTs carry the containers to the corresponding block in the storage yard. When all the workloads are finished, the vessel can depart from the port. If the actual departure time falls behind the estimated one, then a departure delay occurs.

Figure 2 The B-QC-YTAP in two-dimensional plane

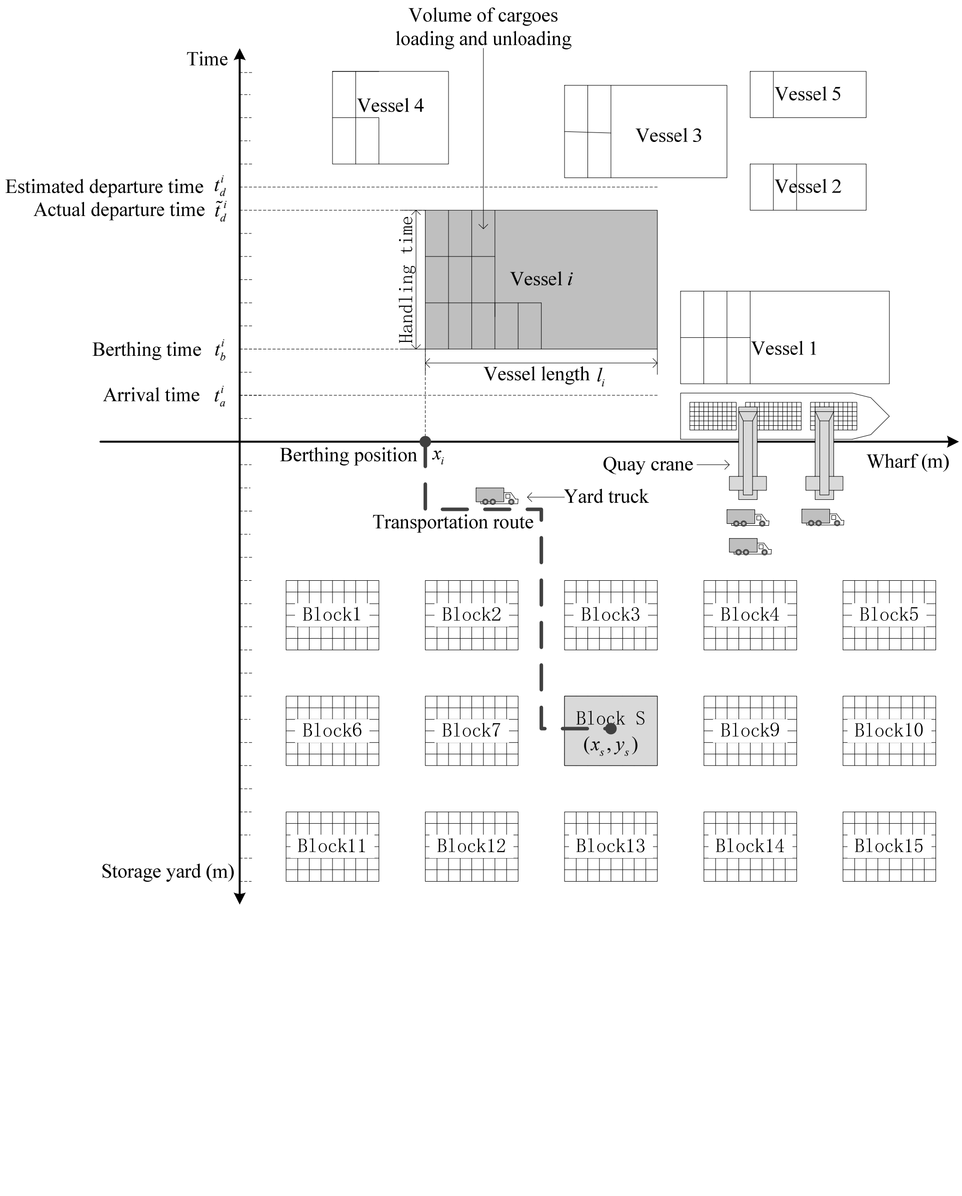


Table 1 Notations used in this study

Parameters	
V	The set of vessels in the planning horizon indexed by i, i', $V = \{1, 2, \ldots, N\}$
T	A set of time segments in the planning horizon indexed by t, $T = \{1, 2, \ldots, T\}$
QC	The set of QCs in the terminal indexed by j, $QC = \{1, 2, \ldots, n\}$
YT	The set of YTs in the terminal indexed by k, $YT = \{1, 2, \ldots, m\}$
S	The set of blocks in storage yard indexed by s
R	The radium of the port area
L	The wharf length of the container terminal
n	The total number of QCs, indexed by j
m	The total number of YTs, indexed by k
l_i	The length of the vessel i
t_a^{i0}	The time for vessel i entering the port area of R knots
t_a^{iL}, t_a^{iU}	The earliest and latest arrival times of vessel i
t_i^d	The estimated departure time of vessel i
$n_i^{\min}$, $n_i^{\max}$	The minimum and maximum numbers of QCs that can be allocated to vessel i
α_i	The carbon emission factors
PO_i	The rated power of the engine for vessel i
LF	The load ratio
EN_i	The number of engines of vessel i
ω	The working energy consumption of a QC per minute (unit: kWh/minute)
ω_0	The energy consumption of a QC per minute for waiting (unit: kWh/minute)
P_{QC}	The productivity of the QC (unit: TEU/minute)
ψ, ψ'	The energy consumption per unit distance for YT' load and empty-load transporting respectively (unit: L/km)
ψ_0	The energy consumption of a YT per minute for waiting (unit: L/minute)
w_i	The handling volume of vessel i
υ	The transport velocity for YTs
(x_s^i, y_s^i)	The coordinate for block s in the storage yard allocated to vessel i
c_i^0, c_i^1	The functional coefficients for the auxiliary and main engine of vessel i, respectively
M	A large positive number
Decision variables	
t_a^i	The arrival time for vessel i
t_b^i	The start time of berthing of vessel i
x_i	The berthing position of vessel i
w_{ij}	The handling volume of QC j undertaking from vessel i
m_i^j	The total number of YTs assigned to QC j which serving vessel i

Table 1 Notations used in this study (continued)

Auxiliary variables	
$\theta_{ii'}$	Equals 1 if vessel i is located in the left of vessel i' in the two-dimensional berth time plane; otherwise 0.
$\eta_{ii'}$	Equals 1 if vessel i is located below vessel i' in the 2-dimensional berth time plane; otherwise 0.
δ_{it}^{j}	Equals 1 if QC j is assigned to vessel i at time step t; otherwise 0.
σ_{it}^{jk}	Equals 1 if YT k is assigned to QC j which serves vessel i at time step t; otherwise 0.
W_{QC}^{ij}	Waiting time that the QC j of vessel i waits for its assigned YTs
W_{YT}^{ij}	Waiting time that the YTs wait for the assigned QC j of vessel i
f_{ij}	The handling time for QC j of vessel i, including loading/unloading time and waiting time
t_{YT}^{i}	The transport time for YT from berthing position x_i to block $s(x_s, y_s)$ in storage yard
$\tilde{t}_d^{i}$	The actual departure time of vessel i
n_i	The total number of QCs assigned to vessel i

The sources for carbon emissions in port area mainly contain two aspects: vessels and port service equipment. Emissions produced by vessels mainly come from the fuel consumption, which markedly depends on the vessels shipping speed in sailing and dwell time in port. And the emissions discharged by port equipment are principally affected by the service efficiency. As analysed before, a reasonable allocation scheme of B-QC-YTAP is the key to carbon emission reduction. On the one hand, the berth allocation plan needs to deal with the three interrelated aspects: berthing time, berthing position, and the departure time. Firstly, vessel's sailing speed can influence its arrival time as well as the berthing time of berth allocation plan; inversely, the berthing plan may result the departure delay of a vessel due to lower service efficiency. Secondly, the QCs and YTs assignment determines the handling time for vessel in port, which directly affects the departure time of vessel. Thirdly, the berthing position influences the distance from wharf to the block in storage yard, i.e., the transportation routing of YTs. These further affect the amount of carbon emissions in port area, not only from vessels but also from the port equipment. On the other hand, in QC-YT assignment problem, the allocated workloads to each QC and the assigned amount of QCs and YTs are the two critical aspects. A balanced task load is of importance because the service time for vessel is determined by the latest finish time of all assigned QCs to the vessel. What's more, a relative proper amount of QCs and YTs are also vital. When too many YTs are assigned to QCs, the reductant YTs must wait for QCs to transfer container from vessel; similarly, if too many QCs are assigned, they must wait for YTs to release the containers, both of which are a waste of resource and result an increase in carbon emissions. Therein, the vessel, berth, QC and YT are an integral system, which requires to establish a joint resource allocation model to solve the B-QC-YTAP.

To simplify the complex B-QC-YTAP, some assumptions are proposed in this study:

1 The handling volume for each vessel is known, and to simplify calculation, the containers are all assumed to be TEUs (20-foot equivalent unit).

2 The berth type we considered is continuous, and the effect of water depth on vessel's berthing position is not taken into account. The berthing position of each vessel is kept unchanged in its entire handling process.

3 Each vessel has a minimum and a maximum number of assigned QCs. The working efficiency of each QC is the same, and the working energy consumption of each QC per move is the same.

4 The YT can transport only one container measured by TEU at a time. The transporting velocity of YTs is the same and the transport time is mainly related with the Manhattan distance from berthing position on wharf to the block in storage yard, which is simplistically expressed by the coordinates distance between berthing position and centre of block.

For the sake of clarity, the notations used in this paper are shown in Table 1.

4 Model development

4.1 Carbon emissions calculation

For detailed emissions inventory calculation approaches, the normal methods include fuel statistics approach and activity-based approach (Song, 2010). In the fuel statistics approach, emissions are estimated based on the amount of the fuel sold or bought, which has poor measurement accuracy. While the activity-based approach calculates the carbon emissions based on the operational data in service activity, and it is generally more accurate due to more detailed data is required such as routing, engine workload, ship speed, location, duration, etc. (Song, 2014), additionally this method can be found in the studies of Kim et al. (2012), Du et al. (2011), Wang et al. (2013b), Ng et al. (2013), Song (2014). In this paper, the latter is adopted and the carbon emissions are calculated by the function of an emission factor multiplying the energy demand in operational level.

The carbon emissions of vessel mainly depend on its fuel consumption. When ship is sailing, the fuel consumption per unit time is affected by sailing speed. Hughes (1996) proposed the *cubic law* claiming that the fuel consumption rate for a vessel (r_F) is a function of sailing speed (s) raised to the third power ($\mu = 3$) as shown in equation (1), where c^0 and c^1 are the functional coefficients for the auxiliary and main engine of the vessel respectively.

While a more general power function is shown by Du et al. (2011) to fit the relationship between the fuel consumption rate and the sailing speed better, in which $\mu \in \{3.5, 4, 4.5\}$, for feeder vessels $\mu = 3.5$, for medium-sized ones $\mu = 4$, and for jumbo ones $\mu = 4.5$, also the authors proved that there exists a most fuel efficient sailing speed s^*. Thus the carbon emissions for a vessel i sailing in the near port area can be derived by equation (2):

$$r_F = c^0 + c^1 \cdot s^{\mu} \tag{1}$$

$$
\begin{aligned}
F_i^1 &= \alpha_1 \times \left[c_i^0 + c_i^1 \left(\frac{R}{t_a^i - t_a^{i0}} \right)^{\mu_i} \right] \times \left(t_a^i - t_a^{i0} \right) \\
&= \alpha_1 \times \left[c_i^0 \left(t_a^i - t_a^{i0} \right) + c_i^1 R^{\mu_i} \left(t_a^i - t_a^{i0} \right)^{1-\mu_i} \right]
\end{aligned} \tag{2}
$$

Equation (2) indicates that the fuel consumption for vessel i is the product of fuel consumption rate and the sailing time, while the total carbon emissions during shipping near port area of vessel i is multiplied by the carbon emission factor for fuel consumption. Here we reference the carbon emission factor (α_1 = 3,110 g/kg-fuel) adopted by COSCO as a standard of calculation (COSCO, 2009), which is popularly accepted and used to conduct the carbon emission analysis (Du et al., 2011; Hu et al., 2014). The terminal operators can ask the vessel for a deceleration to reduce the carbon emission of port area if the vessel's current speed exceeds s^*, or require the ship to accelerate to decrease carbon emissions if its current speed is slower than s^*. It can be noted that the optimal sailing speed is not only producing the least carbon emission to the port area, but also consuming the least amount of fuel for the vessel, therefore the shipping company will certainly accept the suggested speed. The optimal sailing speed of vessel i can be derived by equation (3).

$$
s_i^* = \left(\frac{c_i^0}{c_i^1 (\mu_i - 1)} \right)^{\frac{1}{\mu_i}} \tag{3}
$$

When the vessel arrives at the port, it will moor at the anchor waiting for berthing service until the berth is available. In the whole period during the vessel in port (the duration of arrival until its departure), there is only auxiliary engine works, and the carbon emissions of vessel i while moored can be calculated based on waiting time for berthing. Therein the total carbon dioxide the vessel i discharged in port can be calculated by equation (4) (Hu et al., 2014), where the carbon emission factor α_2 = 683 g/kw-h referred to Hu et al. (2014), PO_i is rated power of the engine of vessel i, LF is a load ratio, EN_i is the number of engines of vessel i, and $(\tilde{t}_d^i - t_a^i)$ is the waiting time for berthing. Among that the $\tilde{t}_d^i$ can be calculated by equations (5) and (6). Equation (5) indicates that the total process time for vessel i is determined by the maximal handling time of the QC assigned to the vessel. The handling time for each QC allocated to vessel i is calculated by equation (6), which is consist of two parts:

a the loading and unloading time for containers

b the waiting time that the QC wait for YTs.

$$
F_i^2 = \alpha_2 \times \left[PO_i \times LF \times EN_i \times \left(\tilde{t}_d^i - t_a^i \right) \right] \tag{4}
$$

$$
\tilde{t}_d^i = t_b^i + \max\{f_{ij}\} \; \forall i \in V, \; j \in QC \tag{5}
$$

$$
f_{ij} = \frac{\delta_{it}^j w_{ij}}{P_{QC}} + W_{QC}^{ij} \;\; \forall i \in V, \; j \in QC, \in T \tag{6}
$$

The carbon emissions discharged by port equipment mainly comes from the QCs and YTs when serve vessel, in which the former is power consumption while the latter is fuel consumption. To comprehensively calculate the volumes of carbon emissions, this paper takes the total carbon emissions produced by QCs and YTs into account not only during the working time for handling containers but also the duration of waiting time caused by unbalance amount assignment among QC and its YTs. The waiting time can be expressed by equations (7)–(9). The equation (7) calculates the idle time for QC waiting for YTs, on the contrary, equation (8) is the idle time of YTs waiting for QC. Therein, the first term in bracket of (7) and (8) aims to compare the handling time for each container operated by QC and YT separately, and the difference represents the idle time of transporting one container, which is multiplied by total handling volume of QC j to indicate the total waiting time of QC j or its YTs serving vessel i. The transporting time for YT from berthing position to its corresponding block in the storage yard is calculated by equation (9).

$$W_{QC}^{ij} = w_{ij} \times \max\left(\frac{2t_{YT}^{i}}{m_i^j} - \frac{1}{P_{QC}}, 0\right) \quad \forall i \in V, j \in QC \tag{7}$$

$$W_{YT}^{ij} = w_{ij} \times \max\left(\frac{1}{P_{QC}} - \frac{2t_{YT}^{i}}{m_i^j}, 0\right) \quad \forall i \in V, j \in QC \tag{8}$$

$$t_{YT}^{i} = \frac{\left|x_i - x_s^i\right| + y_s^i}{\upsilon} \, \forall i \in V \tag{9}$$

Therefore, the carbon emissions produced by QCs can be calculated by equation (10), in which the containers handling time mainly depends on the handled container volumes and the QCs' work efficiency.

$$F_i^3 = \alpha_3 \times \left(\omega \times \frac{w_i}{P_{QC}} + \omega_0 \times \sum_j W_{QC}^{ij}\right) \tag{10}$$

where the term in bracket represents the total electricity consumption (unit: kWh) of QCs assigned for vessel i. The carbon emission factor for electricity consumption is related with the power network region. According to the National Development and Reform Commission of Climate Change, the baseline emission factors for regional power grids in China (Bei, 2015) are shown in Table 2.

Table 2 The baseline emission factors for regional power grids in China (2015)

Region	*North China*	*Northeast*	*East China*	*Central China*	*Northwest*	*South China*
Coefficient (g/kWh)	1,041.6	1,129.1	811.2	951.5	945.7	895.9

While the emission from YTs depend on not only the container handling volumes but also the transportation distance from berthing position to blocks in storage yard. The total carbon emissions corresponding to each vessel i can be calculated by equation (11), where the term in bracket is the total energy consumption for YTs serving for vessel i. The carbon emission factor (Lu et al., 2015).

$$F_i^4 = \alpha_4 \times \left[(\psi + \psi') \times t_{YT}^{i} \times w_i + \psi_0 \times \sum_j W_{YT}^{ij}\right] \tag{11}$$

4.2 Mathematical formulation

Based on the above analysis, the B-QC-YTAP considering carbon emissions in port area can be formulated as:

$$\min f_1 = \sum_{i \in V} \left(F_i^1 + F_i^2 + F_i^3 + F_i^4 \right) \tag{12}$$

$$\min f_2 = \sum_{i \in V} \left[\left(\tilde{t}_d^i - t_d^i \right)^+ + \left(t_b^i - t_a^i \right) \right] / n \tag{13}$$

subject to

$$x_i + l_i \le L \qquad \forall i \in V \tag{14}$$

$$t_b^i \ge t_a^i \qquad \forall i \in V \tag{15}$$

$$t_a^{iL} \le t_a^i \le t_a^{iU} \qquad \forall i \in V \tag{16}$$

$$x_i + l_i \le x_{i'} + M\left(1 - \theta_{ii'}\right) \qquad \forall i, i' \in V, i \ne i' \tag{17}$$

$$\tilde{t}_d^i \le t_b^{i'} + M\left(1 - \eta_{ii'}\right) \qquad \forall i, i' \in V, i \ne i' \tag{18}$$

$$1 \le \theta_{ii'} + \theta_{i'i} + \eta_{ii'} + \eta_{i'i} \le 2 \quad \forall i, i' \in V, i < i' \tag{19}$$

$$\sum_i \delta_{it}^j \le 1 \qquad \forall t \in T, j \in QC \tag{20}$$

$$\sum_i \sum_j \delta_{it}^j \le n \qquad \forall t \in T \tag{21}$$

$$\sum_j \delta_{it}^j = n_i \qquad t = t_b^i \qquad \forall t \in T, i \in V \tag{22}$$

$$n_i^{\min} \le n_i \le n_i^{\max} \qquad \forall i \in V \tag{23}$$

$$\sum_j \delta_{it}^j w_{ij} = w_i \qquad \forall t \in T, i \in V \tag{24}$$

$$\sum_i \sum_j \sum_k \sigma_{it}^{jk} \le m \qquad \forall t \in T \tag{25}$$

$$\sum_k \sigma_{it}^{jk} = m_i^j \qquad \forall i \in V, j \in QC, t \in T \tag{26}$$

$$x_i \ge 0 \qquad \forall i \in V \tag{27}$$

$$\theta_{ii'}, \theta_{i'i}, \eta_{ii'}, \eta_{i'i} \in \{0,1\} \qquad \forall i, i' \in V, i \ne i' \tag{28}$$

$$\delta_{it}^j, \sigma_{ij}^{jk} \in \{0,1\} \qquad \forall i \in V, j \in QC, k \in K, t \in T \tag{29}$$

$$m_i^j, w_{ij} \in N \cup \{0\} \tag{30}$$

The problem is formulated as a multi-objective optimisation issue, and equations (12) and (13) are the two objective functions of this model. In this formulation, the objective (12) is to minimise the total carbon emissions discharged by vessels and port equipment in the port area, in which the four terms are defined in Section 4.1 respectively. The objective function (13) is to minimise the average waiting time in port and departure delay for each vessel so as to improve the service efficiency and shipper's satisfaction. The set of constraints (14) ensures that all vessels must be berthed within the boundary of the wharf. Constraints (15) indicate that the vessel cannot berth before its arrival time. Constraints (16) mean that a vessel's arrival time must satisfy the time-window constraints, which is determined by the vessel's maximal and minimal sailing speed separately. Constraints (17)–(19) enforce the non-overlapping conditions among vessels in the wharf-time space. In particular, constraints (17) ensure that the right side position of vessel i must be less than the left side position of vessel i' if vessel i is located in the left of vessel i', constraints (18) ensure that vessel i' must be moored at the berth after vessel i if vessel i is located below vessel i' in the two-dimensional berth time plane, and constraints (19) ensure that there are one or two position relationships between any two vessels in the two-dimensional berth time plane. Constraints (20) require that any QC can serve at the most one vessel at any time. Constraints (21) limit that the total QCs assigned to vessels at any time step cannot exceed the amount of available. Constraints (22) present the number of QCs assigned to each vessel. Constraints (23) restrict the number of QCs allocated to a vessel at a time step. Constraints (24) state that handling volume required by each vessel must be fulfilled. Constraints (25) limit the number of YTs that can be utilised at any time step. Constraints (26) restrict the number of YTs allocated to a vessel at any time step. And finally, constraints (27)–(30) specify the domains of the variables.

5 Solution algorithm

The two objectives contained in this model are equally important and should be considered together. However, they may be in conflict sometimes, e.g., a slight decrease in departure delay calls for more equipment assigned to vessels, which may increase the total carbon emission in area port. In order to solve the multi-objective B-QC-YTAP (MO-B-QC-YTAP), the trade-off between the two conflicting objectives must be balanced and accordingly the Pareto optimal solutions must be obtained. Over the past decades, lots of multi-objective evolutionary algorithms (MOEAs) have been proposed, among all these MOEAs, the NSGA-II is proved to be one of the most popular methods due to its simplicity, effectiveness, and minimum user interaction (Mousavi et al., 2016). NSGA-II is modified from NSGA by Deb et al. (2002) which overcomes the following three deficiencies:

a high computational complexity of non-dominated sorting

b lack of elitism

c need for specifying the sharing parameter.

NSGA-II shows superiority in the speed of convergence to global Pareto-optimal front and the preservation of the solution's diversity and distribution uniformity, which can well address the proposed MO-B-QC-YTAP model in this paper. Next, we give a brief overview of the NSGA-II. For detailed calculative process, please refer to Deb et al. (2002).

5.1 Initialisation

Considering the characteristic of the solutions and the decision variables, the B-QC-YTAP is represented as a five-vector chromosome, which denotes arrival time, berthing time, berthing position, the allocated workload corresponding to each QC, and the assigned number of YTs for each QC. In the horizontal chromosome, we make a serial number for the vessels according to theirs arrival time. An example of solution chromosome representation is shown in Figure 3. For instance, vessel 2 arrives at time 20, begins to berth at time 30, the berthing position is 100 along the wharf, and the QCs allocated to it are 1, 2, 6 with the corresponding workload 60, 75, 100 TEUs and the corresponding number of YTs 1, 1, 2, separately.

Figure 3 Chromosome representation

		1	2	3	4	5	6
Vessel ID		1	2	3	4	5	6
Arrival time t_a^i		5	20	45	63	75	90
Berthing time t_b^i		8	30	60	70	80	100
Berthing position x_i		80	100	60	10	70	50
Allocated workload for QC w_{ij}	1	0	60	0	0	0	55
	2	0	75	0	30	0	70
	3	40	0	45	45	0	0
	4	80	0	0	35	0	0
	5	0	0	50	0	0	90
	6	0	100	0	0	0	60
	7	0	0	85	0	90	0
Assigned number of YTs for QC m_i^j	1	0	1	0	0	0	1
	2	0	1	0	1	0	2
	3	1	0	1	1	0	0
	4	2	0	0	1	0	0
	5	0	0	1	0	0	3
	6	0	2	0	0	0	1
	7	0	0	2	0	3	0

In this study, the initial population is generated at random. To improve the search efficiency, the domains of variables and some constraints are taken into account when generating the chromosome. The first layer of chromosome about arrival time is generated randomly considering the constraint (16). Similarly, the berthing time is randomly generated under constraint (15), the third layer berthing position under constraints (14) and (27), the next layer 'allocated workload for QC' under constraints (23), (24), and (30), and the final layer under constraints (26) and (30).

5.2 Non-dominated sort

The sorting step follows the same procedure used by Deb et al. (2002). Considering the constraints, each solution can be either feasible or infeasible. Hence the definition that solution *i* dominates solution *j* is as follows:

1. Solution *i* is feasible and solution *j* is infeasible.
2. Solution *i* and *j* are both infeasible, while solution *i* has a smaller overall constraint violation. The constraint violation is calculated by the following steps.

   Step 1 We set the general form for constrained multi-objective optimisation problem with *m* objective functions ($k = 1, 2, \ldots, m$) showed by (31), in which the equality constraints $h_r(\vec{x}) = 0$ can be converted into the inequality ones in (32) and the δ is a small positive value to denote the tolerance value of equality constraints.

   minimise

   $$f_k(\vec{x}), \vec{x} = (x_1, x_2, \ldots, x_n)$$

   Subject to

   $$g_r(\vec{x}) \le 0, r = 1, \ldots, l \tag{31}$$

   $$h_r(\vec{x}) = 0, r = l+1, \ldots, p$$

   $$|h_r(\vec{x})| - \delta \le 0 \tag{32}$$

   Step 2 In a population with *N* individuals, the constraint violation for individual $\vec{x}$ violating constraint *r* can be represented by (33).

   $$G_r(\vec{x}) = \begin{cases} \max\{0, g_r(\vec{x})\}, & 1 \le r \le l \\ \max\{0, |h_r(\vec{x})| - \delta\}, & l+1 \le r \le p \end{cases} \tag{33}$$

   Step 3 Considering the characteristic differences among all constraints, this step is to normalise all of the constraint violations. The normalised total constraint violation for individual $\vec{x}$ is shown in (34), where $G_r^{\max} = \max(G_r(\vec{x}_i))$, $j \in \{1, \ldots, p\}$.

   $$G_{nor}(\vec{x}_i) = \frac{\sum_{r=1}^{p} G_r(\vec{x}_i) / G_r^{\max}}{p}, i = 1, 2, \ldots, N \tag{34}$$

3. Solution *i* and *j* are both feasible, and then *i* dominates *j* when $\forall k \in \{1, 2, \ldots, m\}$, $f_k(\vec{x}_i) \le f_k(\vec{x}_j)$ and $\exists l \in \{1, 2, \ldots, m\}$ $f_l(\vec{x}_i) < f_l(\vec{x}_j)$ are satisfied at the same time.

   Thus all chromosomes in the first non-dominated front is found and make mark for all solutions *i* which dominate the others as $i_{rank} = 1$. When find the next non-dominated front, the solutions of the previous fronts are disregarded temporarily. Repeat the procedure until all the solutions are set into fronts.

5.3 Crowding distance

Crowding distance is defined to evaluate solution fronts of populations in terms of the relative density of individual solutions. Large average crowding distance results better diversity in the population. In a particular front (F) with Z non-dominated solutions, let d_i be the value of crowding distance on the solution i, then the crowding distance is obtained by the following steps. Firstly, set $d_i = 0$ for all the Z solutions. Secondly, sort all objective functions f_k in ascending order. Thirdly, for end solutions in each front, $d_1 = d_z = \infty$. Finally, the crowding distance for d_i are $d_i = d_i + (f_{k_{i+1}} - f_{k_{i-1}})$, ($i$ = 2, 3, …, $Z - 1$).

5.4 Selection, crossover and mutation

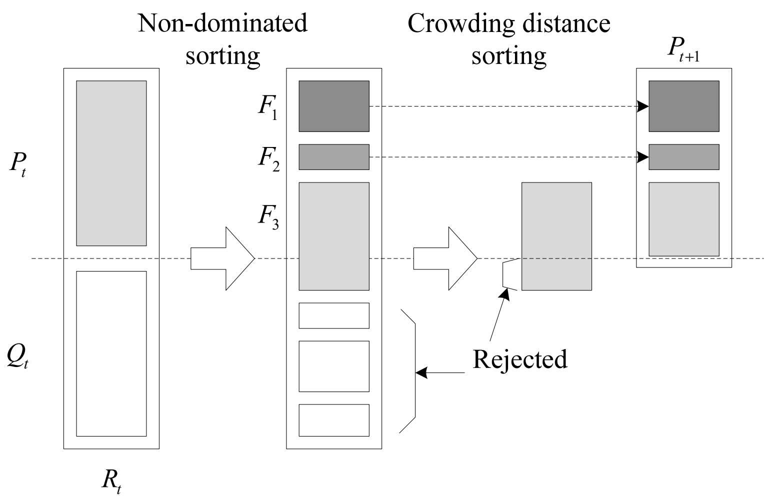
The selection is made by the binary tournament method based on the rank and crowding distance. The selection is carried out with a crowded-comparison-operator $(\prec_n)$. After population sorting, every individual i in the population has two attributes: the non-domination rank (i_{rank}) and the crowding distance ($i_{distance}$). Then we have $i \prec_n j$ if ($i_{rank} < j_{rank}$) or ($i_{rank} = j_{rank}$, and $i_{distance} > j_{distance}$), and the individual i is selected.

The genetic operators used are simulated binary crossover (SBX) (Deb and Agarwal, 1994) and polynomial mutation (Raghuwanshi and Kakde, 2004).

5.5 Population update

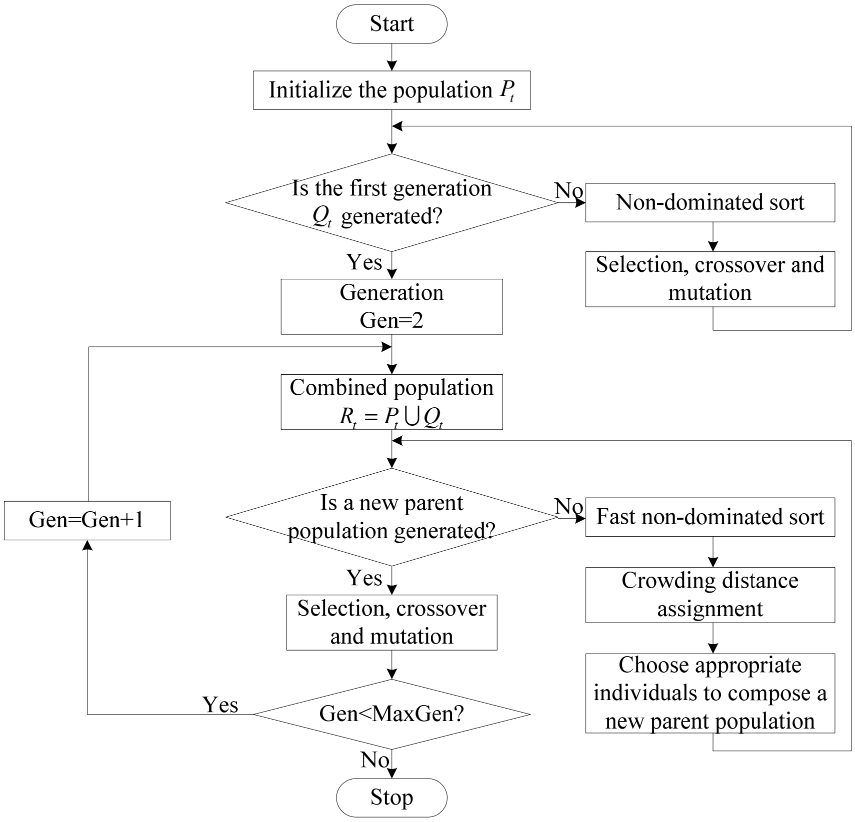
To ensure the elitism, the parents and offspring population are combined, for which the population size is twice of the original one. Then the non-dominated sorting is performed and the chromosomes with higher ranks are selected preferentially. While for the individuals who have the same non-dominated front, the one with large crowding distance is selected until the population size is fulfilled. The sorting process for population update is illustrated as Figure 4.

Figure 4 Population update



According to the above description, the process for NSGA-II can be concluded as the following procedure as illustrated in Figure 5.

Figure 5 The basis procedure for NSGA-II



6 Numerical experiment and computational results

Numerical experiments are conducted to evaluate the efficiency of the proposed model and the algorithm. Then the obtained Pareto optimal solutions are analysed and a result for a specific allocation scheme is showed.

6.1 Numerical experiment

The basic information is shown in Table 3. The length of wharf is L = 1,100 metres long, port area radium R = 20 knots, number of QCs n = 8, number of YTs m = 15, and a planning horizon 24 hours are considered. The wharf is quantified by a unit of 10 m (WU), and the time unit of the planning horizon is 30 min (TU). Due to the unattainable of data, some parameters are randomly generated from uniform distributions defined by the intervals shown in Table 4. In the experiments, 40% of the vessels are in the feeder class, 50% the medium class and 10% the jumbo class. Some other constant initial parameters are set as follows: $LF = 0.5$, $EN_i = 4$, $\omega = 2$ kWh/min, $\omega_0 = 0.5$ kWh/min, $P_{QC} = 36$ TEU/h, $\psi = 1.2$ L/km, $\psi' = 0.8$ L/km, $\psi_0 = 0.05$ L/min, $\upsilon = 20$ km/h, $\alpha_1 = 3{,}110$ $g/kg\text{-}fuel$, $\alpha_2 = 683$ $g/kg\text{-}fuel$, $\alpha_3 = 1{,}041.6$ $g/kg\text{-}fuel$, $\alpha_4 = 2{,}650$ g/L, $M = 10{,}000$. The coordinates for the storage yard blocks allocated to each vessel are shown in Table 5.

Table 3 Data of vessels to port

Vessel ID	t_a^{i0}	t_a^{iL}	t_a^{iU}	t_d^i	w_i	$n_i^{\min}$	$n_i^{\max}$
1	0	1	3	26	248	1	3
2	2	3	7	28	1050	1	5
3	4.5	6	12	30	490	1	3
4	3	4	10	32	560	1	3
5	3.5	4	10	36	525	2	4
6	5	7	16	42	280	1	3
7	12	14	33	53	735	1	3
8	13.5	15	36	50	840	2	5
9	7	10	25	32	210	1	2
10	16.5	19	41	55	735	2	4
11	15	18	43	61	635	1	3
12	22.5	26	44	48	150	1	2
13	18	20	47	54	190	1	3
14	25	27	46	52	180	1	3

Note: To make expression consistent, the data of time has been transformed by the time unit (TU).

Table 4 Some parameters for three vessel classes

Class	$l_i(WU)$	c_i^0	$c_i^1(\times 10^{-4})$	PO_i
Feeder	[8, 21]	[477.4, 719.9]	[151, 245]	[50, 100)
Medium	[21, 30]	[580.7, 718.6]	[37.09, 42.99]	[100,250)
Jumbo	[30, 40]	[491.7, 709.2]	[8.64, 9.72]	[250,425]

Note: Intervals in the table are from Du et al. (2011).

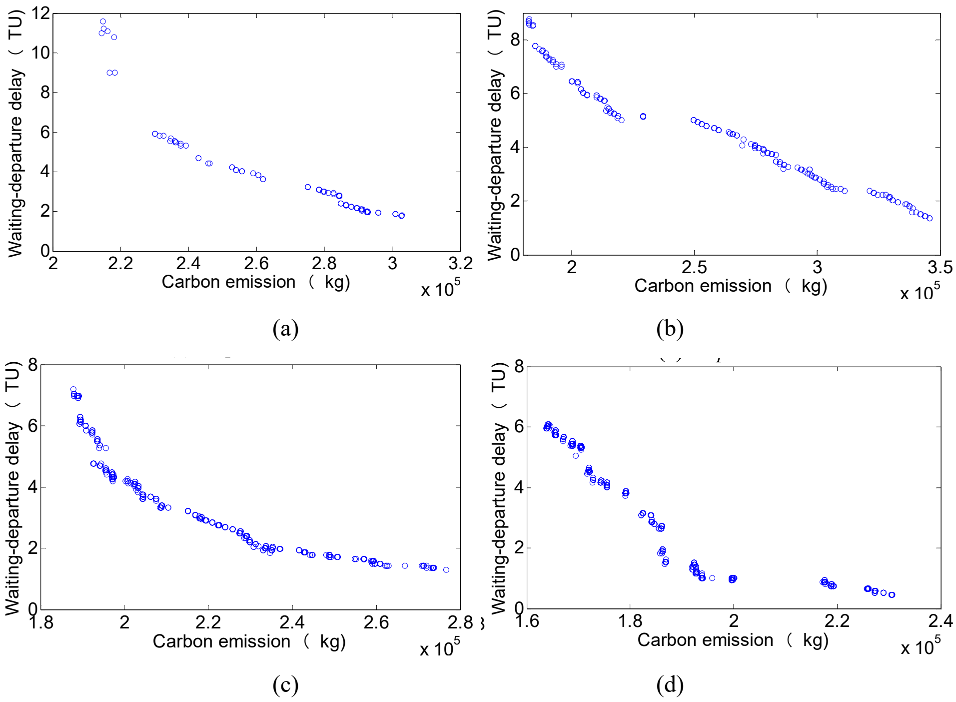
Table 5 The coordinates for the storage yard blocks allocated to vessels

Vessel ID	*1*	*2*	*3*	*4*	*5*
(x_s^i, y_s^i)	(100, 100)	(500, 200)	(700, 200)	(600, 100)	(300, 200)
Vessel ID	*6*	*7*	*8*	*9*	*10*
(x_s^i, y_s^i)	(900, 200)	(300, 100)	(500, 100)	(200, 200)	(900, 100)
Vessel ID	*11*	*12*	*13*	*14*	
(x_s^i, y_s^i)	(100, 200)	(1000, 100)	(800, 200)	(700, 100)	

6.2 Computational results

To implement the NSGA-II, some essential parameters are set. Due to the good robustness of NSGA-II, we select the recommended values for parameters. The crossover probability is $p_c = 0.9$ and the mutation probability $p_m = 0.1$. The distribution indexes for crossover and mutation operators are *mu* = 20 and *mum* = 20 respectively. The tournament size equals 2. Considering the influence of population size *Pop* and generation *Gen* on the result in different problems, we select *Pop* = 300 and *Gen* = 200 as the benchmark and adjust one parameter while keeping the other one unchanged to test the influence of different parameters on result and obtain the most appropriate parameter values. Then we can obtain the Pareto optimal solutions by running the code of NSGA-II in *MATLAB*, in which the influence of population size and generation on the result is shown in Figure 6 and Figure 7.

Figure 6 Influence of population size on the result, (a) *Pop* = 100 (b) *Pop* = 200 (c) *Pop* = 300 (d) *Pop* = 500 (see online version for colours)



From Figure 6 and Figure 7 we can see that the stable, sufficient and evenly distributed Pareto solutions can be obtained as long as the two parameters (pop size and generation) are large enough. Thus the pop size and generation can be adjusted according to the scale of the specific problem. As to the case study in this paper, when *Pop* = 300 [Figure 6(c)] and *Gen* = 200 [Figure 7(c)], the obtained Pareto solutions are satisfying considering the two objectives comprehensively.

Figure 7 Influence of generation on the result, (a) *Gen* = 50 (b) *Gen* =100 (c) *Gen* = 200 (d) *Gen* = 300 (see online version for colours)

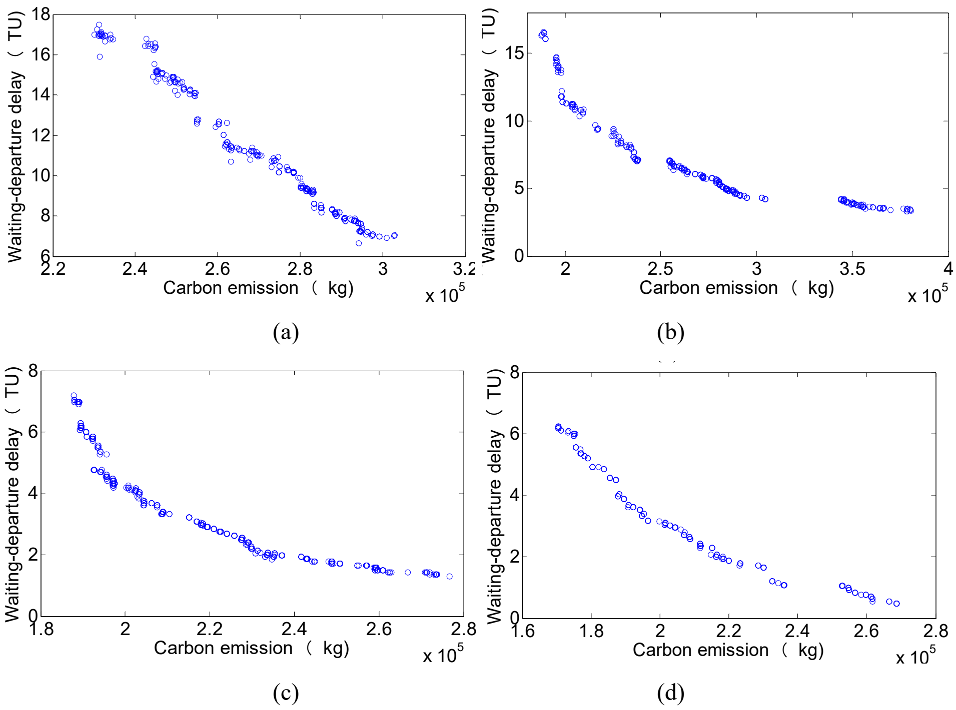


Figure 8 The fitting chart of the two objectives in MO-B-QC-YTAP (see online version for colours)

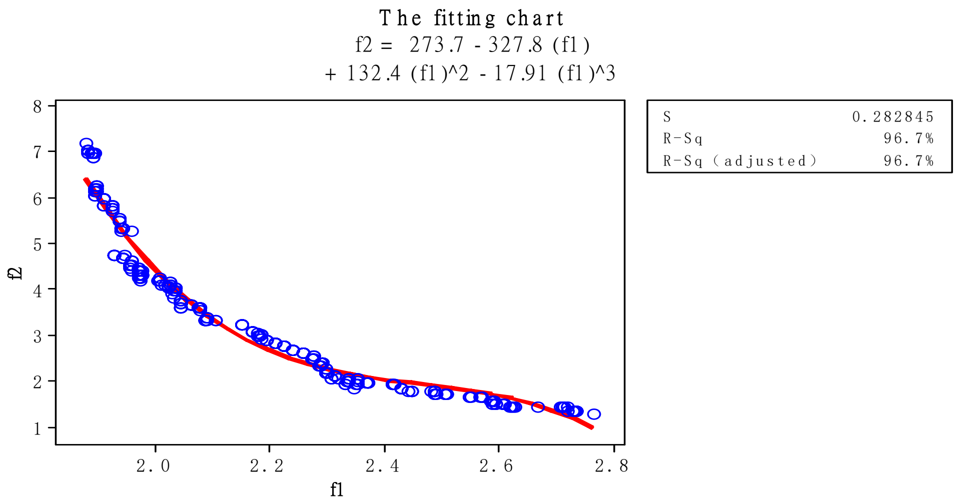


Figure 6(c) and Figure 7(c) show the Pareto solution for the MO-B-QC-YTAP in the case study, which indicate the NSGA-II can obtain effective solutions for the proposed model. From the result we can see that there exists negative correlation between the carbon emission and service efficiency. On one hand, the lower carbon emission in port area will reduce the port service efficiency, that is to say leading to a higher waiting time and departure delay for vessels. On the contrary, if the terminal planners purse high service efficiency, the port must be at the expensive of environment, which will produce much more carbon emissions in port area. The terminal planners need to make a trade-off between the carbon emission cost and the customer opportunity loss caused by long waiting time in port and departure delay. To make the relationship between the two goals more explicit, the cubic curve is selected to fit the two objectives. Figure 8 shows the fitting chart and we can get the fitting result expressed as formula (35), where f_1 and f_2 represent carbon emission (unit: ×105 kg) and waiting-departure delay (unit: TU) correspondingly. Terminal planners can weigh the two goals through fitting curve so as to make decisions much easier.

$$f_2 = 273.7 - 327.8 f_1 + 132.4 f_1^2 - 17.91 f_1^3 \tag{35}$$

7 Conclusions

This work mainly solves the B-QC-YTAP which takes carbon emissions in port area into account. First, a multi-objective optimisation model is established considering carbon emissions and service efficiency. Secondly, the NSGA-II algorithm is introduced to solve the MO-B-QC-YTAP so as to obtain the Pareto solutions. Finally, a numerical experiment is conducted to test the effectiveness of the proposed model.

This paper contributes the literature of green port construction, and the carbon emissions are considered comprehensively in the whole port area including port water area and port land area. Also, the port resources including berth, QCs, YTs are integrated as a whole system to improve the service efficiency as well as reduce the carbon emission in port area.

However, there also exist some limitations in this work. To make the model more practical, the following issues can be further studied. First, the cooperative mechanism between port and shipping lines need to be deep studied because they may provide false information to the other due to their own sake. Second, the YTs transport routes are more complex, the B-QC-YTAP should consider the YTs' transport path design. Finally, this work should be extended to involve multiple terminals in shipping network. These can all be the future research directions and topics.

Acknowledgements

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