Transportation Research Part E 47 (2011) 1021–1037

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Berth allocation considering fuel consumption and vessel emissions

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ARTICLE INFO

Article history:
Received 8 December 2010
Received in revised form 26 March 2011
Accepted 16 April 2011

Keywords:
Berth allocation
Fuel consumption
Emission
Second order cone programming
Port-shipping coordination

ABSTRACT

We propose a more elaborate model on berth allocation considering fuel consumption than before, and overcome the nonlinear complexity by casting it as a mixed integer second order cone programming model. Furthermore, we conduct the vessel emission (in sailing periods) calculation with the widely-used emission factors. Besides, vessel emissions in mooring periods are also analyzed through a post-optimization phase on waiting time. Experimental results demonstrate that the new berth allocation strategy, reflected by the proposed model, is competent to significantly reduce fuel consumption and vessel emissions, while simultaneously retaining the service level of the terminal.

1. Introduction

With the development of economic globalization and the fast growth of international trade, maritime transportation has been playing a more and more important role in the international supply chain. Approximately eight billion tons of international trade goods are transported by sea each year (UNCTAD, 2009). Consistent with this trend, container shipping has gained rapid growth in recent years, and the global container trade volume in 2009 attained 124 million TEUs (source: Clarkson Research Services Limited). In the container shipping system, the shipping lines and the container ports/terminals are the most important enterprises and partners.

As the container terminal business is capital intensive, terminal managers always attempt to improve the utilization of resources involving berths, container yards, quay cranes, yard cranes and container trucks. Among all the resources, berths lie in the kernel position, and the berth plan has a great influence on the quay crane schedule, the yard storage plan and even the truck routing. Both port practitioners and researchers, therefore, have made great efforts for the berth allocation problem (BAP), in order to improve the efficiency of seaside operations and increase the monetary revenue of the port. In addition to the efficiency and economic concerns, high throughput in container ports entails increasing efforts to reduce vessel emissions. It is estimated that vessel emissions, especially the emissions produced by auxiliary engines in the mooring period, make up a major portion of port pollutants. Vessel emissions, like nitrogen oxide (NO_X), sulphur oxide (SO_X) and particulate matters (PM), have contributed to the worsening of the atmospheric environment in port areas, even threatening the health of people living in port cities and coastal communities (Maine Department of Environmental Protection, 2005). Several initiative programs, like the Green Flag program in the Port of Long Beach, have been advocated in the ports of North America.

Meanwhile, shipping lines are making unprecedented efforts to reduce bunker fuel consumption and vessel emissions in the sailing period. For one thing, bunker fuel prices have been increasing a lot in the past few years, and fuel cost has become the overwhelmingly dominant part of operation cost of shipping lines. Shipping lines are trying any possible measure, both

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doi:10.1016/j.tre.2011.05.011

technically and managerially, to reduce fuel consumption. For instance, slowing down the vessels and operating the vessels at economic speed less than 20 knots have been popularly adopted by shipping lines. For another, emissions from vessels have been contributing more and more to the increase of greenhouse gases and harmful pollutants. To mitigate the negative environmental impacts, the legislation for vessel emissions has been strengthened in the past decade. MARPOL Annex VI (IMO, 2005) issued by the international maritime organization (IMO), and EU Directive 2005/33/EC (EC, 2005) issued by the European Commission both came into force in 2005. Both the economic consideration on fuel consumption and the environmental consideration on vessel emissions have far-reaching influences on the strategic choices of shipping lines, including marketing policies, fleet deployment, ship routing and scheduling. Several studies have made their contributions to these decision issues (Fagerholt, 2001; Fagerholt et al., 2010; Norstad et al., 2010; Papadakis and Perakis, 1989; Ronen, 2010). Based on the academic studies, some commercial decision support systems, like TurboRouter (Fagerholt and Lindstad, 2007), have been developed.

As autonomic enterprises, the port and the shipping lines have different business concerns. The port seeks to reduce the vessel emissions for mooring in the port, without lowering the customer service level, by reducing vessel waiting time as much as possible in the berth plan. The shipping lines are concerned about the fuel consumption in the sailing period, and the ensuing vessel emissions. They are slowing down their vessels, while maintaining the scheduling integrity of shipping service. However, the operation plans of the terminal are closely interrelated to the shipping schedules of the shipping lines. On one hand, the arrival times of vessels determined by the shipping schedule are key parameters of the berth plan; on the other hand, Notteboom (2006) demonstrates that port congestion is currently the main cause of shipping schedule unreliability. Delays in one port cascade throughout the whole shipping service and therefore also affect other ports of call (Notteboom and Vernimmen, 2009). This close relationship between the berth plan and the shipping schedule calls for the cooperative efforts of the terminal and the shipping line. The terminal should take into account the operational efficiency of its customers, the shipping lines, instead of planning its operations in isolation. A potential area of coordination between the terminal and the shipping line is controlling the speeds of approaching vessels to determine the arrival times at the terminal. This coordination may ask the vessels to slow down or speed up to make a specific loading/unloading time slot, in order to avoid the terminal congestion, while minimizing the fuel consumption and the vessel emissions, both in the sailing and mooring periods. This coordination can only be achieved through a delicate balance between terminal resources and shipping interests.

With this coordination between the port and the shipping lines in mind, this paper adopts a new berth allocation strategy, and formulates the BAP as a mixed integer nonlinear programming (MINLP) model. To overcome the nonlinear intractability introduced by the consideration of fuel consumption, we cast the original MINLP model as a mixed integer second order cone programming (MISOCP) model, whose competence has been proved by the numerical experiments. Based on the elaborate analysis of fuel consumption, we conduct the emission analysis on CO_2, NO_X and SO_X (in sailing periods) with the help of emission factors. Additionally, vessel emissions in mooring periods, when vessels are anchored in the port, are also evaluated through a post-optimization phase.

Not only does this paper carry out a more elaborate fuel consumption analysis than previous studies on BAP, and propose a novel reformulation skill (second order cone programming, SOCP) to eliminate the nonlinear complexity involved, but also, for BAPs, it firstly conducts a direct quantitative analysis on vessel emissions. This paper is also a good example of studies that aim to reduce vessel emissions in the operational management level, rather than in the strategic level considered by Corbett et al. (2009) and Schrooten et al. (2008).

The remainder of this paper is organized as follows. First, we review the literature closely related to this study. Then we introduce the fuel consumption consideration into the BAP model, and discuss the formulation issues. In the fourth section, we address the calculation method of vessel emissions based on fuel consumption. Finally, we report the experimental results, and draw some concluding remarks.

2. Literature review

A large number of studies on BAPs have been published since the 1990s, to which two classification schemes can generally be applied: (a) the static versus dynamic vessel arrivals, and (b) the discrete versus continuous berthing space. In a static BAP (Li et al., 1998), all the vessels to be served have already been in the port at the beginning of the planning horizon, while in a dynamic BAP (Imai et al., 2001), vessels call at the terminal dynamically over time. The BAP with discrete berthing space (BAPD) (Brown et al., 1994; Imai et al., 2001, 2003) divides the wharf into a collection of partitioned berth segments, while the BAP with continuous berthing space (BAPC) (Kim and Moon, 2003; Li et al., 1998; Lim, 1998) considers the whole wharf as a continuous straight line, and vessels can be berthed at any position along the wharf. The interrelationship between BAPD and BAPC has been discussed by Imai et al. (2005). Imai et al. (2007) also consider a new type of indented berths, which can provide loading/unloading services from both sides of mega-containerships. For a detailed review of recent research on the BAP, we refer the readers to Bierwirth and Meisel (2010).

The studies mentioned above always aim to improve the efficiency of seaside operations, by optimizing some of the desired objectives, such as vessel departure delays, vessel waiting time and the makespan of the berth plan. However, little literature on BAP, with fuel consumption and emission considerations, can be found. From the business background described in the first section, we can see a considerable gap between academic studies and the practice of maritime transportation.

Golias et al. (2009) regard the arrival times of vessels as decision variables instead of previously-known parameters when formulating the BAP. They try to reduce fuel consumption and vessel emissions by minimizing the total waiting time of vessels, based on the assumption that the shorter the waiting time is, the less the fuel consumption and vessel emissions. This analysis method, however, is indirectly biased towards fuel consumption and vessel emissions. And they aim only to reduce the emissions produced when the vessels moor in the port. As a matter of fact, the emissions for sailing are more prominent than those for mooring periods (Schrooten et al., 2008), and, therefore, should be given much more concern.

Lang and Veenstra (2010) also consider the arrival times of vessels as decision variables and minimize the fuel consumption for sailing with a customized simulation tool. Their study provides a direct quantitative analysis on fuel consumption, for the first time, and elucidates that introducing the arrival times as decision variables into the model of the BAP could provide a potential coordination opportunity between terminal operators and shipping lines, which will result in fuel consumption savings in sailing periods. This basic idea is also adopted in our study. However, their study cannot handle the nonlinear function between the fuel consumption rate and the sailing speed. They just simplify the nonlinearity by linear regression. This has been noticed by the authors, and the correction has been regarded as an issue for further research. Additionally, emission analysis is absent in their study.

Alvarez et al. (2010) study the hybrid optimization problem on berth allocation and speed control, and develop a discrete event simulation tool primarily consisting of two components: (a) a discrete-event scheduler, which simulates the interaction between the vessel operators and the terminal planner; and (b) a mixed-integer optimization routine, which simulates the logic of the terminal planner that finds feasible seaside operation plans. The case study shows the competence of the new berth allocation policy in both fuel savings and terminal productivity. They bypass the nonlinearity originating from the consideration of fuel consumption, by discretizing the feasible domain of the sailing speed. This discretization method may lose the calculation accuracy. Moreover, emission analysis is also absent in their study.

3. BAP considering fuel consumption

3.1. A typical BAP model—a constant arrival time (CAT) strategy

In a typical BAP, vessels call at the terminal over time, and terminal planners allocate a berthing position along the wharf and a berthing time in the planning horizon to each vessel, to make the vessels depart as soon as possible. Fig. 1 illustrates the berth allocation in the wharf-time space. The horizontal axis represents the position along the wharf, while the vertical one represents the time axis. Each rectangle represents a vessel to be served. The height of a rectangle denotes the handling time of the corresponding vessel, while the length of a rectangle is the vessel length. The x-axis and the y-axis of the lower left corner of a rectangle correspond to the berthing position and the berthing time of the corresponding vessel.

To make the mathematical model clear, we list the notations used in the following.

Parameters:

- V: The set of vessels under consideration in the berth plan, $|V| = N$.
- L: The wharf length of the container terminal.
- l_i: The length of vessel i, $i \in V$.
- h_i: The handling time of vessel i, $i \in V$.
- a_i^0 The expected arrival time of vessel i, $i \in V$.
- d_i: The requested departure time of vessel i, $i \in V$.
- M: A sufficiently large constant.

Decision variables:

- x_i: The leftmost berthing position of vessel i, $i \in V$.
- y_i: The start time of berthing of vessel i, $i \in V$.

Auxiliary decision variables:

- σ_{ij}: $\sigma_{ij} = 1$ indicates vessel i is positioned left of vessel j along the wharf; $\sigma_{ij} = 0$, otherwise; $i,j \in V$, $i \neq j$.
- δ_{ij}: $\delta_{ij} = 1$ indicates vessel i is positioned below vessel j in the wharf-time space; $\delta_{ij} = 0$, otherwise; $i, j \in V$, $i \neq j$.

As in Kim and Moon (2003), the berth allocation problem is usually formulated as

$$\text{(BAP)} \quad \min \quad \sum_{i \in V} (y_i + h_i - d_i)^+ = \sum_{i \in V} \max(y_i + h_i - d_i, 0) \tag{1}$$

$$\text{s.t.} \quad x_i + l_i \leqslant L, \quad i \in V \tag{2}$$

$$a_i^0 \leqslant y_i, \quad i \in V \tag{3}$$

$$x_i + l_i \leqslant x_j + L(1 - \sigma_{ij}), \quad i,j \in V, \ i \neq j \tag{4}$$

$$y_i + h_i \leqslant y_j + M(1 - \delta_{ij}), \quad i,j \in V, \ i \neq j \tag{5}$$

$$1 \leqslant \sigma_{ij} + \sigma_{ji} + \delta_{ij} + \delta_{ji} \leqslant 2, \quad i,j \in V, \ i < j \tag{6}$$

$$x_i \geqslant 0, \quad \sigma_{ij}, \ \delta_{ij} \in \{0, 1\}, \ i,j \in V, \ i \neq j \tag{7}$$

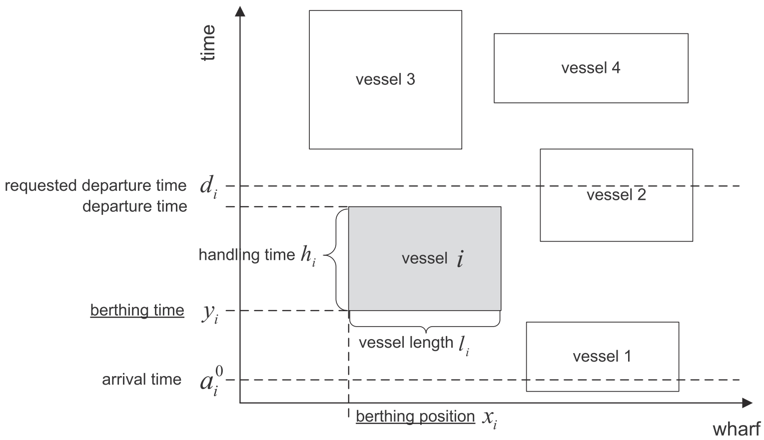

Fig. 1. An example of berth allocation.

In this formulation, the objective (1) is to minimize the total departure delay of all vessels, which is a typical measure of the service level of container terminals and popularly adopted by terminal planners. Constraints (2) ensure that all vessels must be berthed within the boundary of the wharf. Constraints (3) mean that a vessel cannot be berthed before its arrival. Constraints (4)–(6) enforce the non-overlapping conditions among vessels in the wharf-time space. Constraints (7) define the domains of the variables.

It is worth noting that with this BAP formulation, terminal planners allocate the berthing positions and the berthing times to the vessels based on their expected arrival times. That is to say, the terminal operator regards the arrival time of each vessel as a constant known *a priori*. Similar to Golias et al. (2009), we refer to this berth allocation strategy as a *constant arrival time* (CAT) strategy. However, considering the arrival time of a vessel as a decision variable will provide the convenience of optimizing fuel consumption and emissions. This new berth allocation strategy is referred to as a *variable arrival time* (VAT) strategy. The numerical experiments, which will be presented later in this paper, reveal that the VAT strategy significantly outperforms the CAT strategy when taking fuel consumption and vessel emissions into account. With the VAT strategy, we introduce the fuel consumption optimization into the BAP model in next subsection.

3.2. Integrating the fuel consumption optimization into the BAP model

Before introducing the fuel consumption consideration into the BAP model, we first discuss the relationship between the fuel consumption and the sailing speed. Generally speaking, the fuel consumption per unit time for a vessel (r_F) is mainly determined by the sailing speed (s), and the former is positively correlated with the latter. Lang and Veenstra (2010) adopt linear regression for simplicity as below,

$$r_F = c^0 + c^1 \cdot s, \tag{8}$$

where c^0 and c^1 are the regression coefficients.

However, the linear regression in Eq. (8) is not precise enough for the operational-level analysis. Hughes (1996) claims that the fuel consumption rate for a vessel is a function of the sailing speed raised to the third power. This *cubic law* is popularly accepted and used to conduct the fuel consumption analysis in the strategic level (Corbett et al., 2009; Norstad et al., 2010; Ronen, 1982). From the viewpoint of empirical regression, in a more accurate sense, Schrady and Wadsworth (1991) argue that a general power function fits the relationship between the fuel consumption rate and the sailing speed better, i.e.,

$$r_F = c^0 + c^1 \cdot s^\mu, \tag{9}$$

where $c^0, c^1 > 0$ are the constant coefficients, and μ is not necessarily three. Following the suggestions of MAN Diesel & Turbo (2004), a famous manufacturer of marine engines, we choose $\mu = 3.5$ for feeder containerships, $\mu = 4$ for medium-sized containerships, and $\mu = 4.5$ for jumbo containerships in this study.

Based on (9), the fuel consumption of a vessel for a sailing leg with a distance m can be calculated as

$$F = (c^0 + c^1 \cdot s^\mu) \cdot \frac{m}{s} = \frac{c^0 m}{s} + c^1 m \cdot s^{\mu-1}. \tag{10}$$

To make the characteristics of F more clear, we take the derivative of Eq. (10) with respect to s, and yield

$$\frac{dF}{ds} = -\frac{c^0 m}{s^2} + c^1 m(\mu - 1) \cdot s^{\mu-2}, \quad \frac{d^2F}{ds^2} = \frac{2c^0 m}{s^3} + c^1 m(\mu - 1)(\mu - 2) \cdot s^{\mu-3} > 0. \tag{11}$$

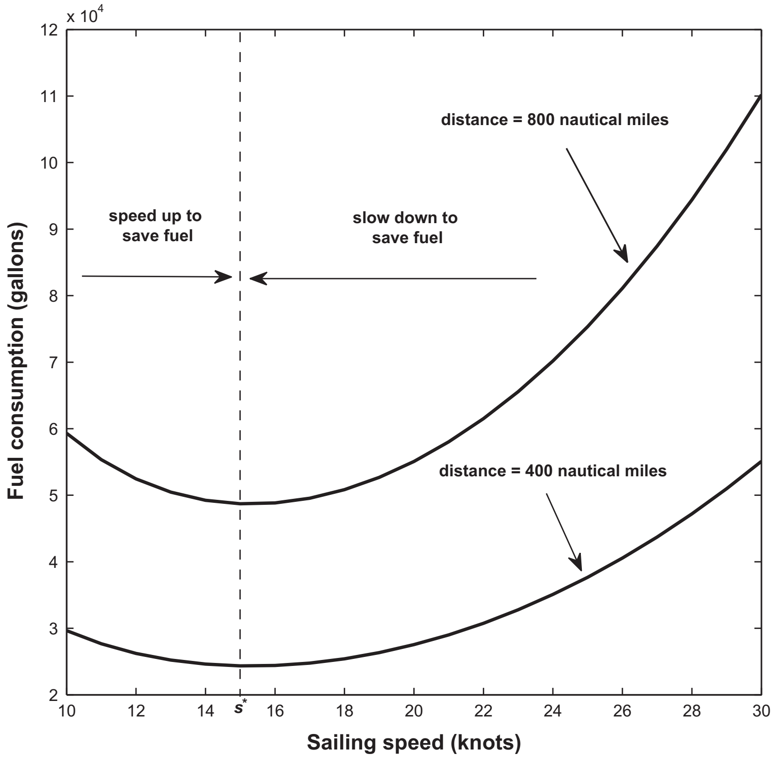

Fig. 2. Fuel use – speed curve for an example vessel.

By solving the equation $dF/ds = 0$, we can obtain the most fuel efficient sailing speed

$$s^* = \left(\frac{c^0}{c^1(\mu - 1)}\right)^{1/\mu} \quad (12)$$

Eqs. (11) and (12) reveal the fact that a vessel can slow down to save fuel if the current sailing speed is faster than s^* (which occurs in most cases in shipping practice), or it can speed up to save fuel consumption if the current sailing speed is slower than s^* (which occurs occasionally in shipping practice). Note that s^* is vessel specific and independent of sailing distance and that the value of s^* is not too sensitive to the parameters inside the μth root in (12). This analytical result is similar to that of model II in (Ronen, 1982). As an example, with $c^0 = 699$, $c^1 = 0.004238$ and $\mu = 4$ (data source: regression for a 5700 TEU containership arriving at Tianjin Port), the fuel consumption for a vessel at different sailing speeds is illustrated in Fig. 2, in which $s^* \approx 15$ knots. Generally, the curve segment where the sailing speed is less than 10 knots can be neglected, since the speeds less than 10 knots are seldom used in shipping practice.

We claim that the logic herein, that vessels can save fuel by speeding up, does not conflict with the traditional logic of saving fuel by slowing down. In the traditional view, a vessel usually cruises at its service speed, as announced by the shipping line, and will not cruise at a speed less than the most fuel efficient speed (s^*), i.e., the curve segment left of the dashed vertical line in Fig. 2 is neglected. Hence slowing down becomes the sole choice for saving fuel. However, in this study, we employ the sailing speed implied by the expected arrival time (a_i^0), not the announced service speed, as the benchmark when we refer to slow-down and speed-up. Meanwhile, through our interview with the practitioners in China Ocean Shipping (Group) Company (COSCO), we discovered that their containerships usually cruise at a speed between 12 knots and 23 knots, and some vessels, especially the feeder containerships, might occasionally cruise to the terminals at speeds less than the most fuel efficient speeds (14–17 knots). So we added the consideration towards the curve segment left of the dashed vertical line in Fig. 2. The experimental result in Section 5 will show that the fuel savings by slow-down is dominant, and speed-up contributes a minor portion to the fuel savings.

Next, we outline the basic idea of the VAT strategy, and integrate the fuel consumption calculation into the BAP formulation. Generally speaking, for vessel i, the shipping line operator can control its arrival time a_i in the interval $[\underline{a}_i, \bar{a}_i]$ by adjusting its sailing speed, where $\underline{a}_i$ and $\bar{a}_i$ are determined by its maximal sailing speed and its minimal sailing speed separately. By considering the arrival time a_i as a decision variable in the BAP, the terminal operator might gain managerial benefits in several aspects. First, the departure delay objective might be further improved compared to that of the typical BAP formulation with the CAT strategy. This can be easily proved by the fact that substituting Constraints (3) with $a_i \leqslant y_i, i \in V$ and $\underline{a}_i \leqslant a_i \leqslant \bar{a}_i, i \in V$ will expand the feasible region of the model (BAP). Second, when the berth usage is busy, the terminal operator may reduce the waiting time of vessels by giving the slow-down suggestions to the vessels that have not arrived at the terminal yet. Meanwhile, the VAT strategy also provides an opportunity to reduce the fuel consumption for the shipping line.

We limit our analysis in this study to a simple business scenario with one port and a certain number of vessels: the vessels under consideration are sailing to the focal port, and will not call other ports before arriving at the focal port. When designing the berth plan, the terminal planner considers the fuel consumption of vessels sailing to the focal port during this berth planning period (e.g., a week).

It is assumed that the berth plan begins at time zero, and the distance from vessel i to the terminal is m_i when the berth plan begins. The fuel consumption of vessel i, therefore, can be calculated by

$$F_i = \left[c_i^0 + c_i^1 \cdot \left(\frac{m_i}{a_i}\right)^{\mu_i}\right] \cdot a_i = c_i^0 \cdot a_i + c_i^1 \cdot m_i^{\mu_i} \cdot a_i^{1-\mu_i}, \tag{13}$$

where $c_i^0, c_i^1 > 0$ are the regression coefficients, and $\mu_i \in \{3.5, 4, 4.5\}$.

Based on the above analysis, the BAP considering fuel consumption can be formulated as

$$\text{(BAPF1)} \quad \min \quad f_1 = \sum_{i \in V} (c_i^0 \cdot a_i + c_i^1 \cdot m_i^{\mu_i} \cdot a_i^{1-\mu_i}) \tag{14}$$

$$\min \quad f_2 = \sum_{i \in V} (y_i + h_i - d_i)^+ \tag{15}$$

s.t. (2), (4)–(7)

$$\underline{a}_i \leqslant a_i \leqslant \bar{a}_i, \quad i \in V \tag{16}$$

$$a_i \leqslant y_i, i \in V \tag{17}$$

Excluding Constraints (7), this model consists of $5N^2/2 + N/2$ constraints and $2N^2 + N$ variables, in which $2N^2 - 2N$ variables are binary. Meanwhile, objectives f_1 and f_2 are both nonlinear, which significantly challenges the branch-and-bound solvers during computation. By substituting each term $(y_i + h_i - d_i)^+$ in (15) with an auxiliary variable t_i, the nonlinear objective f_2 can be transformed to the following linear one.

$$\min \quad f_2 = \sum_{i \in V} t_i \tag{18}$$

$$\text{s.t.} \quad t_i \geqslant 0, \quad i \in V \tag{19}$$

$$y_i + h_i - d_i \leqslant t_i, \quad i \in V \tag{20}$$

However, the nonlinearity in the fuel consumption objective f_1 is also the computational barrier confronting the branch-and-bound solvers. As previously described, the compromise methods, provided by Lang and Veenstra (linear regression) and by Alvarez et al. (speed discretization), may result in calculation inaccuracy. Not avoiding this nonlinearity, we will demonstrate, in next subsection, that f_1 can be equivalently transformed to a linear objective subject to some SOCP constraints, which makes it easy to solve the model to optimality.

3.3. SOCP transformation

SOCP is a state-of-the-art technique in the field of mathematical programming. Fruitful research achievements on SOCP have been gained in the past decade both in theoretical findings and in industrial applications (Alizadeh and Goldfarb, 2003). The efficient interior point algorithm can usually solve SOCP models to optimality in a reasonable time, which stimulates the appearance of dozens of SOCP solvers (Mittelmann, 2010). Some commercial MISOCP solvers, like CPLEX and MOSEK, enhance the practical usage of SOCP when integer variables are involved. It has been proved that various kinds of nonlinear objectives and constraints can be cast as SOCP constraints (Alizadeh and Goldfarb, 2003), which provides the possibility of finding the global optima at an acceptable computational cost. In this subsection, we attempt to cast the nonlinear fuel consumption objective f_1 as a linear objective subject to a group of SOCP constraints and obtain a computationally tractable MISOCP model.

Firstly, by replacing each term $a_i^{1-\mu_i}$ in f_1 with an auxiliary variable q_i, the nonlinearity in the objective can be transferred into the constraints as below:

$$\min \quad f_1 = \sum_{i \in V} (c_i^0 \cdot a_i + c_i^1 \cdot m_i^{\mu_i} \cdot q_i) \tag{21}$$

$$\text{s.t.} \quad a_i^{1-\mu_i} \leqslant q_i, i \in V \tag{22}$$

As $a_i > 0$ for all $i \in V$, (22) is equivalent to

$$1 \leqslant a_i^{\mu_i - 1} q_i, \quad i \in V \tag{23}$$

We will show (23) with a_i, $q_i > 0$ can be equivalently cast as a group of SOCP constraints. For the simplicity of explanation, we take $\mu_i = 4.5$ for example. However, the similar deduction process can be applied to Constraints (23) in cases $\mu_i = 3.5$ and $\mu_i = 4$. In fact, the similar transformation below can also be employed in case $\mu_i = 3$ when the cubic law is adopted.

When $\mu_i = 4.5$, (23) is

$$1 \leqslant a_i^{\frac{7}{2}} q_i, \quad a_i, q_i > 0, \;\; i \in V_J \tag{24}$$

where V_J is the set of jumbo vessels. Square both sides of (24), we obtain

$$1 \leqslant a_i^7 q_i^2, \quad a_i, q_i > 0, \;\; i \in V_J \tag{25}$$

Then (25) can be equivalently expressed by a group of hyperbolic inequalities as follows.

$$u_{i1}^2 \leqslant a_i, \quad u_{i2}^2 \leqslant u_{i1} q_i, \;\; u_{i3}^2 \leqslant a_i u_{i2}, \;\; u_{i4}^2 \leqslant u_{i1}, \;\; 1 \leqslant u_{i3} u_{i4}, \;\; a_i, q_i > 0, \;\; u_{i1}, u_{i2}, u_{i3}, \; u_{i4} \geqslant 0, \;\; i \in V_J \tag{26}$$

By using the fact that a hyperbolic inequality of the form $v_1^2 \leqslant v_2 v_3, \quad v_1, \; v_2, \; v_3 \geqslant 0$ can be rewritten as a SOCP constraint

$$\|(2v_1, v_2 - v_3)\|_2 \leqslant v_2 + v_3, \quad v_1, v_2, v_3 \geqslant 0,$$

where $\|\cdot\|_2$ denotes the Euclidean norm, hyperbolic inequalities (26) can be represented by a group of SOCP constraints as below.

$$\begin{aligned} &\|(2u_{i1}, a_i - 1)\|_2 \leqslant a_i + 1, \quad \|(2u_{i2}, u_{i1} - q_i)\|_2 \leqslant u_{i1} + q_i, \;\; \|(2u_{i3}, a_i - u_{i2})\|_2 \leqslant a_i + u_{i2}, \\ &\|(2u_{i4}, u_{i1} - 1)\|_2 \leqslant u_{i1} + 1, \;\; \|(2, u_{i3} - u_{i4})\|_2 \leqslant u_{i3} + u_{i4}, \;\; a_i, q_i > 0, \;\; u_{i1}, u_{i2}, u_{i3}, u_{i4} \geqslant 0, \;\; i \in V_J \end{aligned} \tag{27}$$

Similarly, when $\mu_i = 3.5$ and $\mu_i = 4$, nonlinear Constraints (23) can be equivalently replaced by SOCP Constraints (28) and (29), respectively.

$$\|(2u_{i1}, a_i - 1)\|_2 \leqslant a_i + 1, \quad \|(2u_{i2}, u_{i1} - q_i)\|_2 \leqslant u_{i1} + q_i, \;\; \|(2, a_i - u_{i2})\|_2 \leqslant a_i + u_{i2}, \;\; a_i, q_i > 0, \;\; u_{i1}, u_{i2} \geqslant 0, \;\; i \in V_F \tag{28}$$

$$\|(2u_{i1}, a_i - q_i)\|_2 \leqslant a_i + q_i, \quad \|(2, a_i - u_{i1})\|_2 \leqslant a_i + u_{i1}, \;\; a_i, q_i > 0, \;\; u_{i1} \geqslant 0, \;\; i \in V_M \tag{29}$$

In (28) and (29), V_F denotes the set of feeder containerships, while V_M the set of medium-sized containerships. It is assumed that $V = V_F \cup V_M \cup V_J$.

Finally, we conclude this subsection by proposing the following MISOCP model of the BAP considering fuel consumption.

$$\begin{aligned} &(\text{BAPF2}) \qquad \text{Objectives}: (18), (21) \\ &\qquad\qquad \text{s.t.} \quad (2), (4)\text{–}(7), (16), (17), (19), (20) \\ &\qquad\qquad\qquad \text{SOCP constraints}: (27)\text{–}(29) \end{aligned}$$

This MISOCP model has both modelling accuracy and computational advantages. Firstly, compared to the models of Lang and Veenstra (2010) and Alvarez et al. (2010), (BAPF2) will lead to a more accurate calculation on fuel consumption in that the general power functions between the fuel consumption rate and the sailing speed is more accurate than the linear functions, and in that the discretization towards the continuous variables (vessel speed) is avoided. This accuracy also ensures the credibility of the emission calculation below, which is based on the calculation of fuel consumption. Secondly, this model overcomes the computational intractability of the MINLP model (BAPF1), and can easily be solved to optimality, which will be proved by the numerical experiments in Section 5.

In fact, as a multi-objective optimization model, (BAPF2) also provides the convenience of managerial trade-offs for terminal planners. In next subsection, we address the solution method to construct the efficient solutions of (BAPF2).

3.4. Solution method

The ε-constraint approach is popular for a bi-objective optimization model in the literature. Its basic idea is to minimize the first objective subject to the constraint that the second objective is not worse than certain values, and solve the whole optimization model as a single objective model. The ε-constraint approach is widely used because of the trade-off convenience provided for the decision maker. With this approach, the decision maker can easily adjust the value of one objective, and investigate the influence of this adjustment on the other objective, in an interactive way (T'Kindt and Billaut, 2006). Using the ε-constraint approach, we propose the following *Procedure 1* to construct the efficient frontier of model (BAPF2).

Procedure 1: ε-constraint approach for model (BAPF2)

Step 1. Calculate the ideal points and the nadir points.
$f_1^{ideal} = \min\{f_1|(2),(4)-(7),(16),(17),(27)-(29)\}$,
$f_2^{ideal} = \min\{f_2|(2),(4)-(7),(16),(17),(19),(20)\}$,
$f_1^{nadir} = \min\{f_1|(2),(4)-(7),(16),(17),(19),(20),(27)-(29), f_2 = f_2^{ideal}\}$,
$f_2^{nadir} = \min\{f_2|(2),(4)-(7),(16),(17),(19),(20),(27)-(29), f_1 = f_1^{ideal}\}$.
Step 2. Initialize $\mathcal{F} = \{(f_1^{ideal}, f_2^{nadir}), (f_1^{nadir}, f_2^{ideal})\}$, and $\varepsilon_2 = f_2^{nadir} - \tau$.
Step 3. **While** $\varepsilon_2 > f_2^{ideal}$ **do**
Step 3.1. Solve $p_1(\varepsilon_2) \triangleq \min\{f_1|(2),(4)-(7),(16),(17),(19),(20),(27)-(29), f_2 \leqslant \varepsilon_2\}$.
Add the optimal solution $(f_1^*(p_1), f_2^*(p_1))$ into $\mathcal{F}$.
Step 3.2. Set $\varepsilon_2 = f_2^*(p_1) - \tau$.
Step 4. Remove the dominated points in $\mathcal{F}$. Output $\mathcal{F}$ as the set of efficient solutions.

4. From fuel consumption to vessel emissions

In this section, we will discuss the calculation of vessel emissions based on the fuel consumption. In order to make it better understood, we will start from the background introduction related to vessel emissions.

Maritime transport has been making a considerable contribution to the economic growth of the world. However, at the same time, sea-going vessels are emitting more and more pollutants such as CO_2, NO_X, SO_X and PM. The share of maritime emissions in the total emission volume will definitely increase with the sharp decreasing trend of emissions arising from other transport modes (road, rail and inland navigation). This can be explained by the fact that more and more stringent emission standards and fuel specifications are imposed on road transport, railway traffic and inland navigation, and by the fact that the long lifespan of vessels slows down the turnover of marine vessel technologies. To make things worse, maritime emissions have been widely ignored by national air quality programs since maritime emissions are always produced in international waters. In the calculation methodology of the Intergovernmental Panel on Climate Change (IPCC), emissions from sea-going vessels are not attributed to countries due to the discrepancy between the place where fuels are bought and the place where emissions are produced (IPCC, 1997).

With the authority of the Kyoto protocol, IMO has made a great effort to reduce vessel emissions. MARPOL Annex VI, adopted by IMO in 1997, entered into force on May 19, 2005. MARPOL Annex VI is the main regulation for the prevention of air pollution from ships, and the revision efforts are still going on. The latest substantial amendments on MARPOL Annex VI were adopted in the 58th session (October 6–10, 2008) of IMO Marine Environment Protection Committee (MPEC). The revised MARPOL Annex VI covers the issues from the regulations on fuel specifications and engine technologies to market mechanisms (IMO, 2008b). Meanwhile, IMO is also aware of the importance of reducing emissions through the managerial measures in the operational level, such as speed control, fleet management and the improvement on cargo handling operations (IMO, 2008a). In such a sense, our study, aiming to reduce maritime emissions by speed control when designing the berth plan, is highly consistent with the efforts of IMO.

Now we discuss the calculation method of vessel emissions. The absence of reporting methodologies and monitoring programs disable the precise calculation of vessel emissions like the calculation of car emissions. Generally, until now, vessel emissions are roughly calculated by the fuel consumption and the emission factors as

$$\text{vessel emissions (g)} = \text{fuel consumption (kg)} \times \text{emission factor (g/kg-fuel)}. \tag{30}$$

Due to the absence of measurement equipments of emission factors installed in vessels, emission factors of vessel fuel are always chosen in a generic sense. In practice, the emission factors issued by the authorities like IPCC and IMO are widely used. For instance, COSCO adopts the emission factors in Table 1 in the calculation of vessel emissions (COSCO, 2009). In this study, we also adopt the emission factors in Table 1, except that we fix the emission factor of NO_X as 87 g/kg-fuel, since the majority of sea-going vessels have 2-stroke main engines and 4-stroke auxiliary engines installed, and the fuel consumption of main engines is dominant.

Table 1
Emission factors adopted by COSCO.

Emission	Emission factor (g/kg-fuel)	Reference
CO_2	3110	IMO MEPC/29/18/DEC.1989
NO_X	87 (2-stroke engine) 57 (4-stroke engine)	Clean Cargo Working Group Environmental Performance Survey Appendix II
SO_X	60	

As far as the fuel consumption in Eq. (30) is concerned, one should keep in mind that the fuel consumption for sailing is dominant compared to that for mooring periods, which is consistent with the fact that the emissions for sailing are more dominant than those for mooring periods. In fact, the CO_2 emissions for sailing represent about 74% of the total volume of CO_2 for marine vessels, the NO_X and SO_X emissions about 79% (Schrooten et al., 2008). We, therefore, claim that it is a credible practice to calculate the vessel emissions based on the fuel consumption result produced by model (BAPF2).

5. Numerical experiments

Numerical experiments are conducted to evaluate the performance of the proposed VAT strategy and the corresponding model (BAPF2). All optimization models concerned are formulated by YALMIP (Löfberg, 2004) in MATLAB environment and solved by IBM ILOG CPLEX 12.2. *Procedure 1* for efficient solutions in Section 3.4 is also implemented via YALMIP. The numerical experiments are all performed on a personal computer with Intel Core i5 2.67 GHz CPU and 4 GB RAM.

The experiments consider a wharf of 1200 m long on a weekly basis. Without loss of rationality, we use 10 m as a wharf unit (WU), and 30 min as a time unit (TU). In order to conduct intensive analysis, we carry out the experiments on 10 test problems with 10–28 vessels. For each problem, 10 instances are randomly generated as follows. Some basic parameters are randomly drawn from uniform distributions defined by the intervals shown in Table 2. In last column, s_i^0 denotes the initial sailing speed of vessels when the berth plan begins. $a_i^0 \sim U[0, 336 - h_i]$, $m_i = a_i^0 s_i^0/2$. $\underline{a}_i = 2 \times m_i/24$, $\bar{a}_i = 2 \times m_i/10$ for feeder vessels, $\underline{a}_i = 2 \times m_i/28$, $\bar{a}_i = 2 \times m_i/12$ for medium-sized vessels and $\underline{a}_i = 2 \times m_i/30$, $\bar{a}_i = 2 \times m_i/14$ for jumbo vessels. As suggested by (Kim and Moon, 2003), d_i is randomly generated by $d_i = a_i^0 + h_i \cdot U[1, 2]$. Note that for each instance, 60% of the vessels belong to the feeder class, 30% the medium class and 10% the jumbo class.

Actually, in Table 2, c_i^0 and c_i^1 in the first row are the 95% confidence intervals of c_i^0 and c_i^1 for the fuel-speed regression of a 2800 TEU containership, while c_i^0 and c_i^1 in the second row are for a 5700 TEU containership. For jumbo containerships, owing to no available experimental data, we use the fuel-speed data, of a 5700 TEU containership, where the speed is more than 18 knots as a workaround when we conduct the fuel-speed regression. Note that this might underestimate the fuel savings by speed control for jumbo containerships and make the experimental results below a bit *conservative*.

In order to assess the performance of the VAT strategy adopted by model (BAPF2), we use the CAT strategy adopted by model (BAP) as the benchmark. We first investigate the economic benefits on fuel consumption and the environmental benefits on vessel emissions. Then we conduct some experiments on waiting time to further assess the vessel emissions for mooring in the port.

5.1. Economic analysis on fuel consumption

In this subsection, we employ *Procedure 1* to obtain the efficient frontier for each instance, and investigate the trade-off between the departure delay and the fuel consumption. Especially, we will give an intensive analysis on fuel consumption.

The efficient frontier for instance 51 with 20 vessels is shown in Fig. 3. As the benchmark, the solution obtained by the CAT strategy, denoted by (f_1^{CAT}, f_2^{CAT}), is also illustrated in Fig. 3. As shown in Fig. 3, the right-most solution in the efficient frontier, $(f_1^{nadir}, f_2^{ideal})$, dominates the benchmark solution (f_1^{CAT}, f_2^{CAT}). If the terminal planner adopts the berth plan indicated by $(f_1^{nadir}, f_2^{ideal})$, the shipping operators can reduce the fuel consumption from 1723.28 kgal to 1595.29 kgal. That is, 127.99 kgal of fuel can be saved via the VAT strategy. It is clear that the terminal planner will not be interested in the solutions located in the left part of the efficient frontier, since the total departure delay is too high to accept. We boxed the managerially acceptable part of the efficient frontier and enlarged it in a sub-diagram on the upper right corner of Fig. 3. In this sub-diagram, f_1^{1h} denotes the minimal fuel consumption subject to the constraint that the average departure delay for each vessel is not more than 1 h (*one-hour-departure-delay limit*), while f_1^{2h} denotes the minimal fuel consumption when the average departure delay for each vessel is not more than 2 h (*two-hour-departure-delay limit*). With the one-hour-departure-delay limit and the two-hour-departure-delay limit, the shipping lines can save $f_1^{CAT} - f_1^{1h} = 166.85$ and $f_1^{CAT} - f_1^{2h} = 191.25$ kgal of fuel, respectively. Since the VAT strategy can solve the objective values for the departure delay of all instances to zero (also the optimal value), we also refer to f_1^{nadir} as the minimal fuel consumption with the *zero-hour-departure-delay limit*.

Similar analysis can be carried out towards the efficient frontier of instance 23 (14 vessels) shown in Fig. 4. In addition, an appealing result in Fig. 4 is that $(f_1^{nadir}, f_2^{ideal})$ dominates the benchmark solution (f_1^{CAT}, f_2^{CAT}) on both objectives. Besides the advantage on the fuel consumption, the VAT strategy can also reduce the value of the departure delay from 5 h obtained

Table 2
Some basic parameters for different vessel classes.

Class	l_i (WU)[a]	h_i (TU)[b]	c_i^0	c_i^1	s_i^0 (knots)[c]
Feeder	[8, 21]	[6, 30]	[477.4, 719.9]	[0.0151, 0.0245]	[10, 24]
Medium	[21, 30]	[10, 54]	[580.7, 718.6]	[0.003709, 0.004299]	[12, 28]
Jumbo	[30, 40]	[20, 38]	[491.7, 709.2]	[0.000864, 0.000972]	[14, 30]

[a] *Data Source*: Meisel and Bierwirth (2009).
[b] *Data Source*: Based on Meisel and Bierwirth (2009).
[c] *Data Source*: Based on the data collected from COSCO.

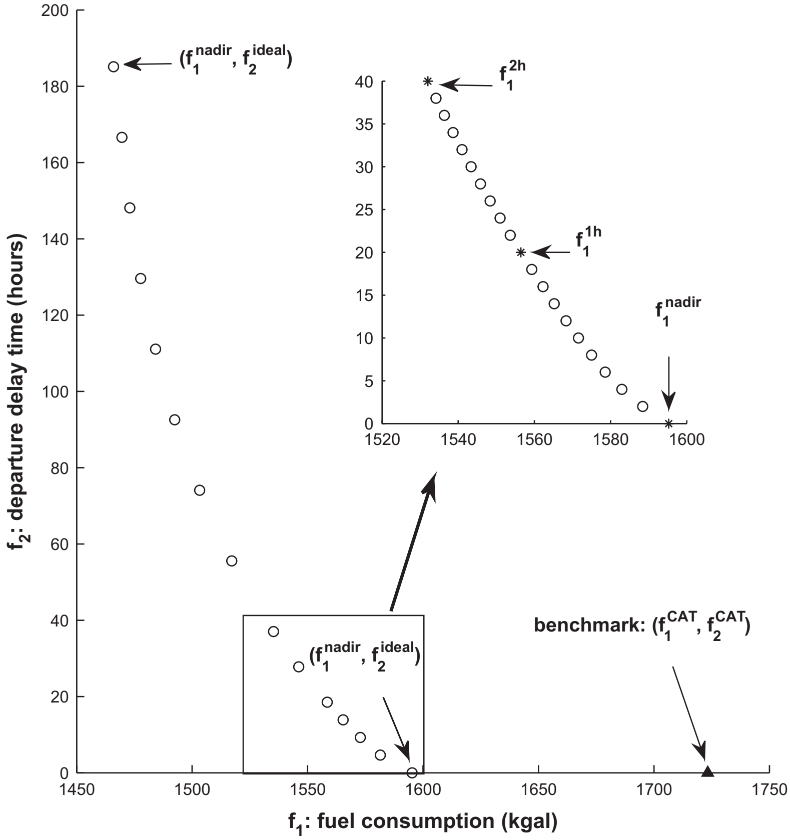

Fig. 3. Efficient frontier for instance 51.

by the CAT strategy to zero. This can be explained by the fact that considering the arrival time a_i as a decision variable may expand the feasible region, which has been addressed above in Section 3.2.

The detailed result for the 10 problems is collected in Table 3. For each problem, all the entries are the averages over 10 instances, except that for problem 10, the averages over eight instances are listed, since two of 10 instances ran out of memory in CPLEX. Aside from the fuel consumption under the three departure delay limits, Table 3 also reports the corresponding fuel savings in the parentheses. With the CAT strategy, model (BAP) for each instance can be solved to optimality in 15 s. When it turns to the VAT strategy and model (BAPF2), for 93 out of the 98 test instances (100 instances excluding two instances running out of memory), the interesting right part of the efficient frontier can be drawn in 500 s. This splendid computation performance originates from the SOCP transformation in Section 3.3.

From Table 3, we can see that for the departure delay objective, the VAT strategy is not worse than the CAT strategy, or even better than the CAT strategy in problem 3 and problem 9. The slightness of the departure delay revealed by Table 3 is in accord with the reality that, in regular operations, the berth productivity in most container terminals is competent to guarantee the integrity of shipping schedules. Meanwhile, for the problem with 20 vessels, the VAT strategy can save 157.07/236.66/287.90 kgal of fuel, respectively, under the three different departure delay limits. For the problem with 28 vessels, the VAT strategy can dramatically save 187.43/275.77/328.71 kgal of fuel. It can be concluded that the VAT strategy is competent to keep (and sometimes improve) the service level of the terminal, while significantly saving fuel consumption. Relaxing the limit on the departure delay can substantially save the fuel consumption further.

One may argue that with the CAT strategy, if the terminal operator shares the planned berthing time y_i^{CAT} with the shipping line, the vessel operator can also proactively control the sailing speed to save fuel when $y_i^{CAT} > a_i^0$ is observed. We refer to this strategy as *the CAT strategy with information sharing*. Next, we report the experimental results of fuel consumption in Table 4, to compare the CAT strategy with and without information sharing, and to compare the CAT strategy with information sharing to the VAT strategy (joint scheduling between the terminal and the shipping line is the main idea of the VAT strategy, even though information sharing is also implied). In this table, $save1 = f_1^{CAT} - f_1^{CATIS}$, $save2 = f_1^{CATIS} - f_1^{nadir}$, and $impr = (f_1^{CAT} - f_1^{CATIS})/(f_1^{CAT} - f_1^{nadir})$, where f_1^{CATIS} denotes the fuel consumption via the CAT strategy with information sharing.

From Table 4, we can see that (a) the information sharing between the terminal and the shipping line can save a large amount of fuel consumption, and that (b) the fuel saving power of the information sharing is much weaker than that of the joint scheduling via the VAT strategy: the former is 38.36% of the latter on average. However, from a practical point

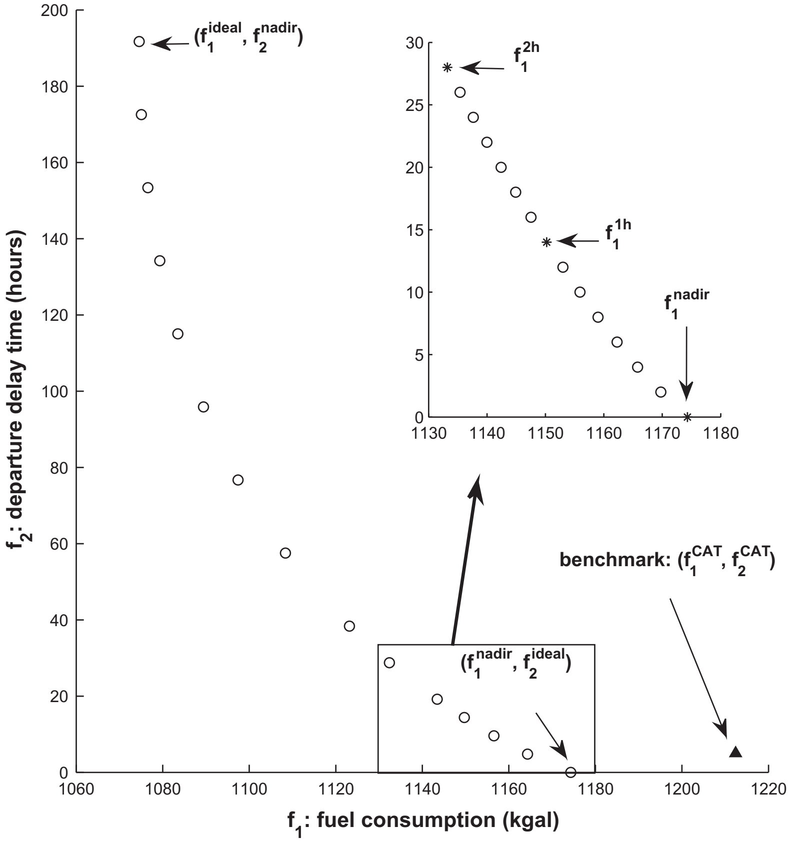

Fig. 4. Efficient frontier for instance 23.

Table 3
Comparison on the departure delay and the fuel consumption.

Problem No. (#vessels)	Benchmark (CAT)		VAT			
	f_2^{CAT}	f_1^{CAT}	f_2^{ideal}	f_1^{nadir} (save[a])	f_1^{1h} (save[b])	f_1^{2h} (saves[c])
1(10)	0	1060.28	0	992.58(67.70)	957.63(102.65)	933.69(126.59)
2(12)	0	1153.35	0	1092.70(60.65)	1062.48(90.87)	1043.88(109.47)
3(14)	1	1391.76	0	1316.80(74.96)	1285.51(106.25)	1263.20(128.56)
4(16)	0	1686.18	0	1568.46(117.72)	1519.39(166.79)	1489.83(196.35)
5(18)	0	1869.16	0	1724.55(144.61)	1648.10(221.06)	1606.34(262.82)
6(20)	0	2273.07	0	2116.00(157.07)	2036.41(236.66)	1985.17(287.90)
7(22)	0	2167.15	0	2043.08(124.07)	1975.58(191.57)	1939.45(227.70)
8(24)	0	2465.95	0	2300.23(165.72)	2213.67(252.28)	2166.46(299.49)
9(26)	0.2	2393.55	0	2237.71(155.84)	2167.24(226.31)	2124.15(269.40)
10(28)	0	2797.27	0	2609.84(187.43)	2521.50(275.77)	2468.56(328.71)

Unit for f_1: kgal; unit for f_2: h.
[a] $f_1^{CAT} - f_1^{nadir}$.
[b] $f_1^{CAT} - f_1^{1h}$.
[c] $f_1^{CAT} - f_1^{2h}$.

of view, the CAT strategy with information sharing is pretty attractive, since the implementation will be much easier and cheaper.

In order to give a more visible explanation, we divide the values of the fuel savings by the number of vessels for each problem in Table 3. We obtain that, for each vessel arrival, the shipping lines can save [5.05, 8.03]/[7.57, 12.28]/[9.12, 14.60] kgal of fuel, respectively, under the three departure delay limits. According to the average price, 468.25 $/MT, of four kinds of marine fuel (IFO380, IFO180, LS380 with 1.00% sulphur, LS180 with 1.00% sulphur) in August 2010 (BunkerWorld Rotterdam, 2010), the shipping lines can save [7458, 11,859]/[11,180, 18,136]/[13,469, 21,562] US dollars for each vessel call.

Table 4
Fuel saving power of "information sharing" versus "joint scheduling" (unit: kgal).

Problem No. (#vessels)	CAT	CAT + Info Sharing		VAT		*impr* (%)
	f_1^{CAT}	f_1^{CATIS}	*save*1	f_1^{nadir}	*save*2	
1(10)	1060.28	1050.71	9.57	992.58	58.13	14.14
2(12)	1153.35	1126.39	26.96	1092.70	33.69	44.45
3(14)	1391.76	1353.09	38.67	1316.80	36.29	51.59
4(16)	1686.18	1639.46	46.72	1568.46	71.00	39.69
5(18)	1869.16	1814.60	54.56	1724.55	90.05	37.73
6(20)	2273.07	2215.26	57.81	2116.00	99.26	36.81
7(22)	2167.15	2122.76	44.39	2043.08	79.68	35.78
8(24)	2465.95	2400.96	64.99	2300.23	100.73	39.22
9(26)	2393.55	2327.16	66.39	2237.71	89.45	42.60
10(28)	2797.27	2719.25	78.02	2609.84	109.41	41.63
AVG	–	–	–	–	–	38.36

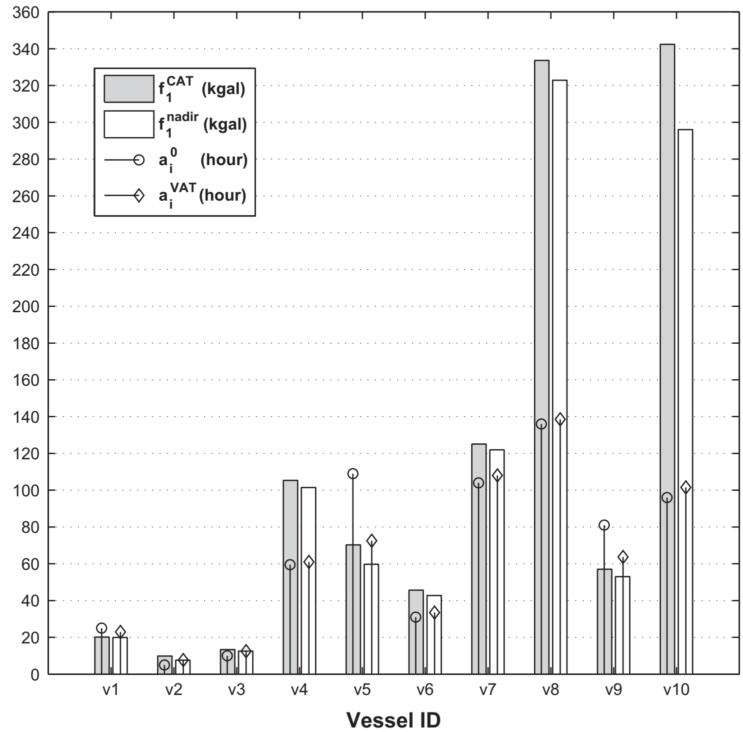

Fig. 5. Fuel consumption and arrival time of each vessel for instance 10.

This economic savings will be magnified when taking into account the future global levy scheme proposed by IMO. COSCO, which is a leading shipping line in the world, believes that this will significantly cut down its fuel cost if the VAT strategy can be widely adopted by container terminals.

In Section 3.2, we obtain the analytical result that both slow-down and speed-up can be adopted as the fuel-saving operation. To verify this analytical result, we recorded the fuel consumption and the arrival time of each vessel for all test instances. The experimental result of a typical instance, instance 10 with ten vessels, is drawn in Fig. 5, in which a_i^{VAT} is the arrival time of vessel i in the berth plan indicated by $(f_1^{nadir}, f_2^{ideal})$. It can be seen that vessels 2, 3, 4, 6, 7, 8 and 10 gain in their fuel savings, compared to the CAT strategy, by delaying their arrivals ($a_i^{VAT} > a_i^0$ in Fig. 5), i.e., slowing down the sailing speeds. Besides, vessels 1, 5 and 9 reduce their fuel consumption by speed-up ($a_i^{VAT} < a_i^0$ in Fig. 5). In total, 70.01 kgal of fuel reduction can be ascribed to slow-down, while 14.73 kgal to speed-up. We also report the fuel savings by slow-down and speed-up over 10 problems in Fig. 6, which shows that, for our test problems, 81–91% of the fuel savings originate from slow-down and 9–19% from speed-up. It can be concluded that the fuel savings originating from slow-down are dominant; additionally, the fuel savings originating from speed-up are also not negligible.

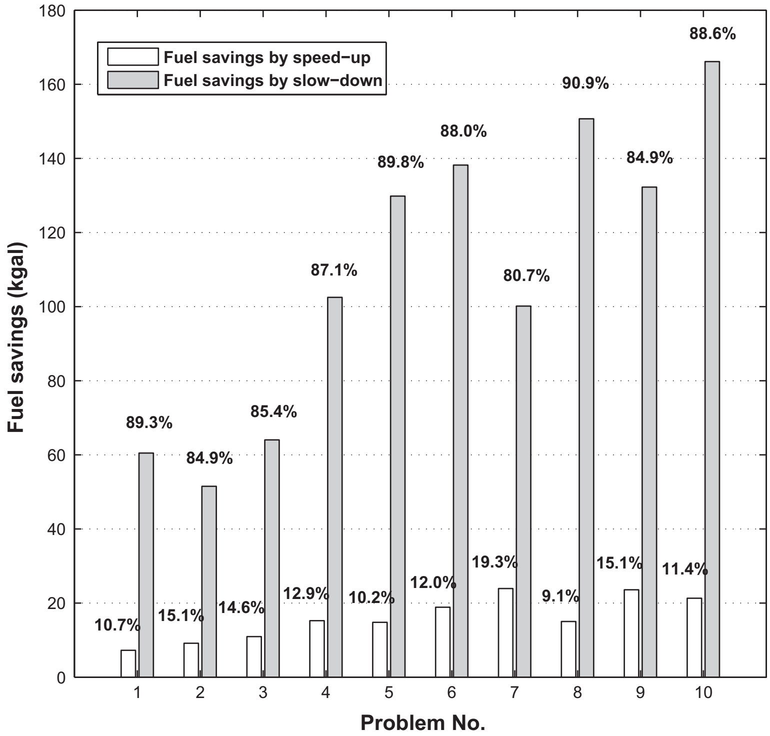

Fig. 6. Fuel savings by slowdown versus by speedup.

Table 5
Average emission reduction for each vessel arrival by the VAT strategy (unit: ton).

Departure-delay limit	CO_2 reduction	NO_X reduction	SO_X reduction
Zero-hour-departure-delay limit	[49.58, 78.80]	[1.39, 2.20]	[0.96, 1.52]
One-hour-departure-delay limit	[74.28, 120.46]	[2.08, 3.37]	[1.43, 2.32]
Two-hour-departure-delay limit	[89.48, 143.22]	[2.50, 4.01]	[1.73, 2.76]

5.2. Environmental analysis on vessel emissions

In this subsection, we aim at evaluating the effects of the VAT strategy on maritime emissions. All the tasks for emission calculation are just to multiply the fuel savings in Table 3 by the emission factors in Table 1, according to Eq. (30). The metric equivalent "1 gallon fuel = 3.154 kg fuel" is used in this study.

Given the fuel savings and the number of vessels for each problem shown in Table 3, we calculate the average emission reduction for each vessel arrival and collect the result in the form of intervals in Table 5. As an example, with the VAT strategy, the reduction of CO_2 emissions for each vessel arrival can achieve $74.28 \sim 120.46$ tons on average under the one-hour-departure-delay limit. With the result in Table 5, every shipping line can roughly evaluate its emission reductions based on the number of terminal calls in a management period, which makes this study enter into practice from the theoretical analysis. COSCO takes an interest in the data shown in Table 5. In 2008, COSCO had an emission volume of 16,094,701 tons CO_2, 325,483 tons NO_X and 274,564 tons SO_X, about 65% of which was contributed by the containership fleet that holds more than 190 containerships (COSCO, 2009). Based on the data in Table 5, the VAT strategy will substantially reduce the emission volume of COSCO and help shipping lines, like COSCO, fulfil their environmental responsibilities.

5.3. Waiting time and the vessel emissions for mooring periods

The waiting time for a vessel is the duration between its arrival time and its berthing time, during which it moors in the terminal waiting for its berth. The waiting time of vessel $i(w_i)$, whose arrival time is a_i and berthing time is y_i, can be represented as

$$w_i = y_i - a_i. \tag{31}$$

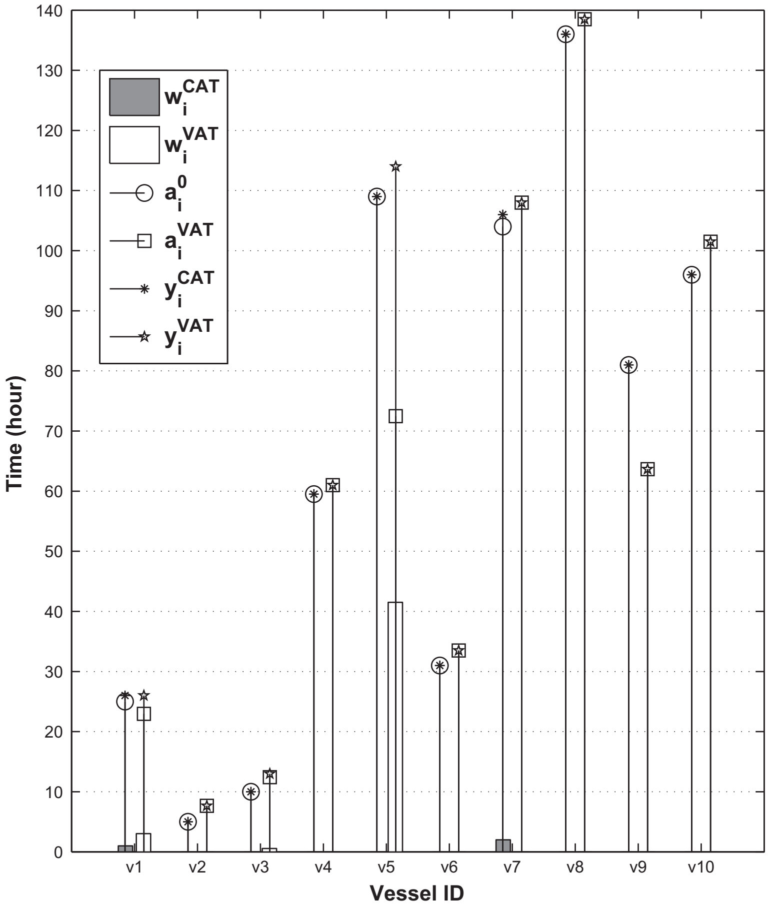

Fig. 7. Waiting time of each vessel for instance 10.

Waiting time not only has a considerable economic influence on the cost of operating vessels and the opportunity cost of carrying other cargoes, but also has a substantial influence on the volume of vessel emissions during mooring periods in the port. Golias et al. (2009), therefore, use the waiting time as a surrogate measure of the volume of vessel emissions in the port.

The acceptable efficient solutions of model (BAPF2) can almost always lead to a shorter departure delay time, large fuel savings and a big volume of emission reductions, based on the above experimental results. However, our experiments also suggest that the solutions cannot assure a short waiting time, which is inconsistent with the intuition that, with the VAT strategy, the terminal operator may reduce the waiting time by giving the slow-down suggestions to the vessels that have not arrived at the port. This inconsistency can be traced back to the following facts. (a) As described in Section 3.2 and verified in Section 5.1, some vessels may speed up, approaching the most fuel efficient speeds to reduce the fuel consumption, which makes the arrivals earlier. As an example, we plot the waiting time, the arrival time and the berthing time of each vessel for instance 10 in Fig. 7. In this figure, $w_i^{CAT}, a_i^0, y_i^{CAT}$ denote the waiting time, the arrival time and the berthing time by the CAT strategy, respectively ($w_i^{CAT} = y_i^{CAT} - a_i^0$), while $w_i^{VAT}, a_i^{VAT}, y_i^{VAT}$ correspond to $(f_1^{nadir}, f_2^{ideal})$ by the VAT strategy ($w_i^{VAT} = y_i^{VAT} - a_i^{VAT}$). In Fig. 7, the waiting time is illustrated with the bar chart, while the arrival time and the berthing time with the stem chart. It can be seen that vessel 5 speeds up to save fuel and arrives at the port 36.5 h ahead of the expected arrival time, while vessel 1 arrives 2 h ahead of time. We are, thus, not surprised to see that the waiting time incurred by vessels 1 and 5 is dominant in the total waiting time. (b) Minimizing the departure delays generally imposes loose constraints on berth allocation, which can be proved, to some extent, by the values of f_2^{CAT} and f_2^{ideal} in Table 3. The loose constraints permit the existence of dozens of berth plans with objectives $(f_1^{nadir}, f_2^{ideal})$. However, the optimization process of CPLEX might terminate at one of the solutions in which the value of y_i is large.

In light of the second reason for long waiting time, it is straightforward to add a post-optimization procedure on waiting time based on the efficient solution $(f_1^{nadir}, f_2^{ideal})$, by replacing Constraints (16) and (17) in (BAPF2) with $a_i = a_i^{VAT}$ and $a_i \leqslant y_i \leqslant y_i^{VAT}$. The objective of the post-optimization procedure is to minimize the total waiting time. We refer to this post-optimization procedure as *PostOpt1*, hereafter. The waiting time by the three strategies (CAT, VAT, VAT + *PostOpt1*)

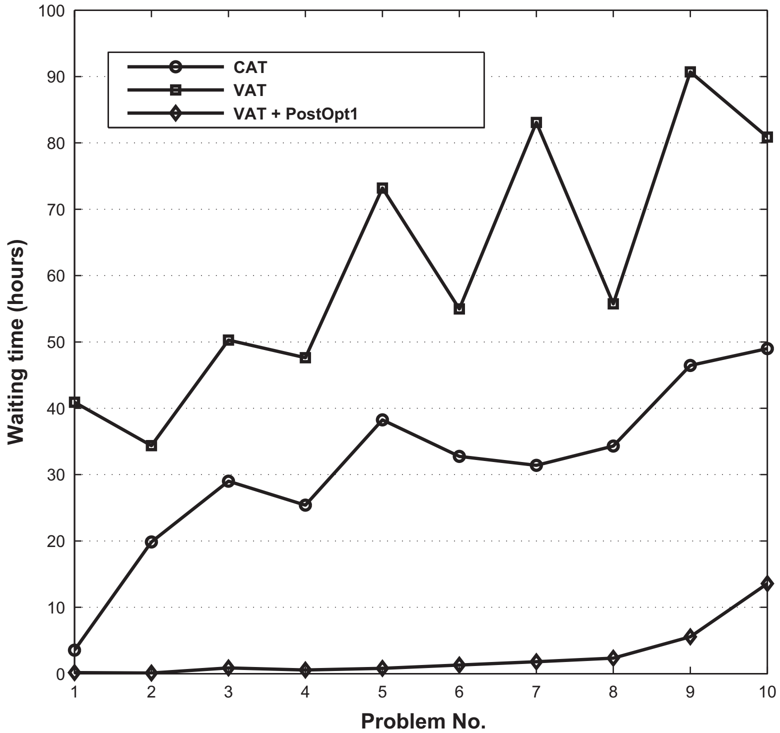

Fig. 8. Comparison on waiting time among three strategies.

are illustrated in Fig. 8. It can be seen that the VAT strategy, if the post-optimization on waiting time is included, is also competent to keep waiting time at an extremely satisfactory level.

We held a discussion on the VAT strategy with some terminal planners in Tianjin Port, and they pointed out an unreasonable phenomenon, from the viewpoint of practice, that some vessels (say vessels 1 and 9 in instance 10, shown in Fig. 5) saved a trivial amount of fuel by speed-up, which might be offset by the possible waiting time resulting from the arrival time earliness, since some outbound containers to be loaded may not have arrived at the container yard yet. Following their suggestions, we revised the post-optimization procedure *PostOpt1* by postponing the arrival times, to some extent, of the vessels that save less than 5 kgal of fuel by speed-up (vessel set V^{ET}). The difference from *PostOpt1* is that for any vessel $j \in V^{ET}$, we use the constraint $a_j = \min(a_j^0, y_j^{VAT})$ instead of $a_j = a_j^{VAT}$. This post-optimization procedure is referred to as *PostOpt2* in this paper. We illustrate the performance of *PostOpt2* over 10 problems in Fig. 9. It can be seen that the VAT strategy with *PostOpt2* can not only keep the waiting time at an extremely satisfactory level, but can also drag down the arrival earliness to a lower level, at the cost of a slight loss of fuel savings for sailing. Compared with *PostOpt1*, the post-optimization procedure *PostOpt2* reflects more practical considerations and is, thus, preferred by the terminal planners in Tianjin Port.

Based on the close relation between waiting time and the emissions for mooring in the port, we arrive at an amazing conclusion that the VAT strategy can not only help shipping lines reduce the vessel emissions for sailing, but also help ports control the vessel emissions in mooring periods to a low level. Note that although the emissions for mooring in ports is dominated by the emissions for sailing in volumes, the former is a more sensitive subject and has been catching more attention, since it has a great and visible impact on the atmospheric environment in ports and the health of people living in port cities.

6. Conclusion

With the VAT strategy, we propose a MINLP model for the BAP considering fuel consumption, by integrating the general power function relation between the fuel consumption rate and the sailing speed. To overcome the computational challenge, we cast it as a MISOCP model. Furthermore, based on the more accurate calculation of the fuel consumption and the widely used emission factors, we evaluate the emission mitigation effect of the VAT strategy. Experiments show that the VAT strategy can considerably cut down the fuel consumption of the shipping line and the vessel emissions, such as CO_2, NO_X and SO_X for sailing. From the viewpoint of the port, by implementing the berth plan generated by the VAT strategy, the terminal operator can keep the service level in a high degree. Meanwhile, the emissions during mooring periods in the port can also be reduced to an extremely small volume. In other words, the VAT strategy creates a coordination mechanism which can produce win–win economic and environmental benefits for both the port and the shipping line. Note that some minor modifications towards the model (BAPF2) could accommodate to the berth allocation in a rolling horizon setting.

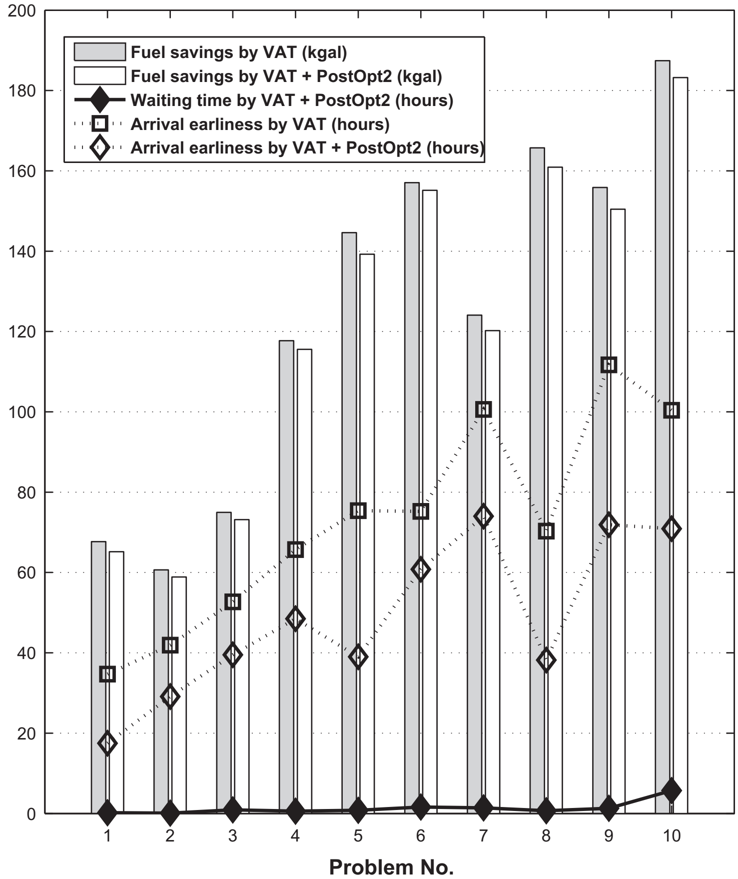

Fig. 9. Performance of the post-optimization procedure PostOpt2.

The managerial insight into the VAT strategy is the collaborative scheduling policy between the port and the shipping line. The ships convey the basic info (the ship length, loading/unloading workload, the requested departure time, its distance away from the port, its available maximal/minimal operating speed, etc.) to the port proactively; based on the information related to the ships to be berthed, the port designs a berth plan which takes into account both the concerns of the port (the customer service level, vessel emissions for mooring) and the concerns of the shipping line (fuel consumption and vessel emissions for sailing); then, the port transmits the suggested vessel arrival times back to the ships. Besides the win–win economic and environmental benefits that drive the VAT strategy, it must be noted that information sharing and collaboration motivation are prerequisites.

The contributions of this paper to the literature can be summarized in two aspects. (a) We have made the fuel consumption calculation in the BAP more elaborate than ever before, and shown that this nonlinear complexity can be handled by the SOCP technique, which is newly arising in the field of mathematical programming. It is worthy to be noted that the fuel consumption rate in practice may vary significantly, depending on the technical features of vessels (engines, sizes, capacities, etc.), which will lead to various power functions by empirical regression. In fact, it can be proved that besides the cases $\mu_i = 3, 3.5, 4, 4.5$, the nonlinearity involved in Eq. (9) can be handled by SOCP, as long as μ_i can be represented as the form $\mu_i = \frac{p}{q}(p, q \in Z_+, p > q > 0)$. It is this elaborate calculation of fuel consumption that makes it possible to conduct the emission calculation precisely. (b) As far as we know, for the BAP, this is the first study that carries out a direct, quantitative analysis on maritime emissions.

There are also some limitations in this study. First, the BAP model in this study does not consider quay crane assignment, which has an impact on the handling time of vessels. Second, in the practice of the container terminal, outbound containers are often concentrated in the container yard 2 or 3 days before their carrying ship arrives at the port. Under the new circumstances created by the VAT strategy, we should also coordinate the cargo concentration plan with the berth allocation, to ensure the arrivals of the outbound containers before the carrying ship is berthed. However, this study does not take the cargo concentration plan into account. Finally, this study only considers a terminal and its client carriers. This may be extended to involve multiple terminals in a port, and even multiple ports in the shipping network. Overcoming these limitations and improving the models could be the topics for future research.

Acknowledgements

This work is partly supported by the National Natural Science Foundation of China under Grants 70772052, 70871090 and 71002077 and the General Research Grant (GRF) 9041491 (CityU 113609) from the RGC Hong Kong SAR. During this study, professional suggestions and the knowledge on fuel consumption and vessel emissions were provided by Mr. Jie Dong of COSCO, whose valuable help is fully appreciated. We also thank two anonymous referees and the editor-in-chief, Prof. Wayne K. Talley, for their constructive comments and suggestions.

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