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Mixed-time mixed-integer linear programming for optimal detailed scheduling of a crude oil port depot

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ABSTRACT

Crude oil port depots are key hubs in oil trade and thus play a vital role in the crude oil supply chain. Based on the characteristics of the scheduling system in an oil port depot, the development of a precise schedule is essential for handling asynchronous upstream supply and downstream market demand, thereby reducing operation cost as well as the impact of market fluctuations. Most previous studies focused only on the depot system, and few have taken the export transport scheduling into consideration. In this study, the diversity of crude oil storage modes, complexity of operations, and variety of transportation modes are considered. To minimize the total operation cost, a mixed-time representation based on a mixed-integer linear programming model is established. Finally, three real cases in a crude oil port depot in China are studied, and the monthly schedules of the depot are developed. Compared with previous algorithms, this method yields more accurate results in a considerably shorter time with improved computational stability.

1. Introduction

1.1. Background

In the current energy market, crude oil is still a major energy source for power generation and transportation. According to statistics, global crude oil trade has reached a volume of 6.1222×10^7 billion barrels per day (BP, 2016). Crude oil port depots (COPDs) are key hubs for harbor storage of unloaded oil and subsequent shipment to refineries for distillation based on the downstream oil market. Thus, COPDs play a vital role in the crude oil supply chain. Developing a precise COPD schedule is crucial to handling asynchronous upstream port supply and downstream market demand, thereby reducing operation cost as well as the impact of market fluctuations on the downstream industry chain. Several studies have demonstrated the significance of effective COPD management in reducing the emission of greenhouse gas (Wu et al., 2017) and increasing enterprise-wide benefits (Menezes et al., 2017).

As fluctuations in crude oil trading result in fluctuations in the throughput of large COPDs, and the interaction of discrete-event and continuous processes (which was introduced in detail by Zhang et al. (2017a), Kelly et al. (2017a), Wu et al. (2016), and Duan et al. (2015)) is quite complex, COPD scheduling is also considerably complex owing to the diversity of crude oil storage modes, complexity of operations processes, and variety

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Nomenclature

Abbreviations

CNY Chinese Yuan
COPD Crude oil port depot
GA Genetic algorithm
MILP Mixed-integer linear programming
MINLP Mixed-integer nonlinear programming

Sets and indices

$t \in T$ Time window, t_{max} is the maximum number of time windows
$p, p' \in P$ Oil types
$i \in I$ Refinery
$k \in K$ Transportation mode
$a, a' \in A_p$ Type p oil tanks at COPD
$n \in N_p$ Receiving plan for type p oil
$z \in Z_{i,p}$ Demand plan for type p oil of refinery i

Continuous parameters

$C_{TRi,k,p}$ Unit volume cost of transportation mode k for type p oil from COPD to refinery i (CNY)
$C_{TBi,k,p}$ Unit cost of transport initiation (CNY/km m^3)
C_{DS} Unit cost of tank operation (CNY)
C_{TF} Berthing per hour (CNY/h)
$L_{i,k}$ Export distance from COPD to refinery i using transportation mode k (km)
M A sufficiently large number
$V_{Tmaxp,a}$ Upper capacity of tank a of type p oil (m^3)
$V_{Tminp,a}$ Lower capacity of tank a of type p oil (m^3)
$V_{DEMAi,p,z}$ Demand volume of refinery i for type p oil during demand plan z (m^3)
V_{UVKk} Unit transporting volume using transportation mode k (m^3)
$V_{SHMAp,n}$ Carry volume of tanker of type p oil during receiving plan n (m^3)
$Q_{EOmaxk,p}$ Upper limit of transporting rate when transportation mode k is used to transport type p oil (m^3/h)
$Q_{EOmink,p}$ Lower limit of transporting rate when transportation mode k is used to transport type p oil (m^3/h)
Q_{DOmaxp} Upper limit of flow rate when receiving type p oil (m^3/h)
Q_{DOminp} Lower limit of flow rate when receiving type p oil (m^3/h)
$\tau_{EXBp,i,z}$ Start time of demand plan z of refinery i for type p oil (h)
$\tau_{EXNi,p,z}$ End time of demand plan z of refinery i for type p oil (h)
$\tau_{DEBp,n}$ Arriving time of oil tanker carrying type p oil of receiving plan n (h)
$\tau_{MDBp,a}$ Start time of maintenance operation of type p oil tank a (h)
$\tau_{MDNp,a}$ End time of maintenance operation of type p oil tank a (h)

Discrete parameters

N_{Kmaxk} Maximum number of available vehicles of transportation mode k

Continuous variables

$V_{OUEt,i,k,p,a}$ Export volume of type p oil from tank a transported using transportation mode k to refinery i in time window t (m^3)
$V_{OUSt,p,a,a'}$ Switching volume of type p oil from tank a to tank a' in time window t (m^3)
$V_{ADIt,p,n,a}$ Receiving volume of type p oil to tank a in receiving plan n in time window t (m^3)
$V_{TINt,p,a}$ Inventory of type p oil tank a at the start time of time window t(m^3)
$V_{EXACt,i,p,z}$ Accumulated export volume of type p oil to refinery i in demand plan z at the start time of time window t (m^3)
$V_{DEACt,p,n}$ Accumulated receiving volume of type p oil in receiving plan n at the start time of time window t (m^3)
$\tau_{DEMt,p,n}$ Accumulated harboring time in receiving plan n at the start time of time window t (h)
$\tau_{DENp,n}$ End time of receiving plan n for type p oil (h)
τ_t Start time of time window t (h)

Discrete variable

$N_{Kt,i,k,p}$ Number of vehicles from COPD to refinery i transporting type p oil using transportation mode k in time window t

Binary variables

$B_{AEXt,i,k,p}$ Binary variable of transport initiation. If COPD adopts transportation mode k exporting type p oil to refinery i at the start time of time window t, $B_{AEXt,k,p} = 1$; otherwise $B_{AEXt,k,p} = 0$

$B_{EXt,i,k,p,a}$ Binary variable of export operation. If type p oil tank a starts exporting oil to refinery i using transportation mode k at the start time of time window t, $B_{EXt,i,k,p,a}=1$; otherwise $B_{EXt,i,k,p,a}=0$

$B_{SWt,p,a,a'}$ Binary variable of switching operation. If type p oil tank a switches oil to another tank in time window t, $B_{SWt,p,a,a'}=1$; otherwise $B_{SWt,p,a,a'}=0$

$B_{INt,p,n,a}$ Binary variable of receiving operation. If type p oil tank a receives oil from an oil tanker in time window t, $B_{INt,p,n,a}=1$; otherwise $B_{INt,p,n,a}=0$

$B_{SEXt,p,a}$ Binary variable of export operation. If type p oil tank a exports oil during time window t, $B_{SEXt,p,a}=1$; otherwise$B_{SEXt,p,a}=0$

$B_{SSWt,p,a}$ Binary variable of switching operation. If type p oil tank a starts switching oil to tank a' at the start time of time window t, $B_{SSWt,p,a}=1$; otherwise $B_{SSWt,p,a}=0$

$B_{SINt,p,a}$ Binary variable of receiving operation. If type p oil tank a starts receiving oil from an oil tanker in receiving plan n at the start time of time window t, $B_{SINt,p,a}=1$; otherwise $B_{SINt,p,a}=0$

$B_{TEXBt,i,p,z}$ Binary variable of export start time. If the start time of time window t is equal to the start time of demand plan z of refinery i for type p oil, $B_{TEXBt,i,p,z}=1$; otherwise $B_{TEXBt,i,p,z}=0$

$B_{TEXNt,i,p,z}$ Binary variable of export end time. If the start time of time window t is equal to the end time of demand plan z of refinery i for type p oil, $B_{TEXNt,i,p,z}=1$; otherwise $B_{TEXNt,i,p,z}=0$

$B_{EXMt,i,p,z}$ Binary variable of export time. If time window t is contained in the horizon of demand plan z of refinery i for type p oil, $B_{EXMt,i,p,z}=1$; otherwise $B_{EXMt,i,p,z}=0$

$B_{TDEBt,p,n}$ Binary variable of receiving start time. If the start time of time window t is equal to the start time of receiving plan n for type p oil, $B_{TDEBt,p,n}=1$; otherwise $B_{TDEBt,p,n}=0$

$B_{TDENt,p,n}$ Binary variable of receiving end time. If the start time of time window t is equal to the end time of receiving plan n for type p oil, $B_{TDENt,p,n}=1$; otherwise $B_{TDENt,p,n}=0$

$B_{DEMt,p,n}$ Binary variable of receiving time. If time window t is contained in the horizon of receiving plan n for type p oil, $B_{DEMt,p,n}=1$; otherwise $B_{DEMt,p,n}=0$

$B_{TMDBt,p,a}$ Binary variable of maintenance start time. If the start time of time window t is equal to the start time of maintenance plan of type p oil tank a, $B_{TMDBt,p,a}=1$; otherwise $B_{TMDBt,p,a}=0$

$B_{TMDNt,p,a}$ Binary variable of maintenance end time. If the start time of time window t is equal to the end time of maintenance plan of type p oil tank a, $B_{TMDNt,p,a}=1$; otherwise $B_{TMDNt,p,a}=0$

$B_{MTt,p,a}$ Binary variable of maintenance time. If the time window t is contained in the horizon of maintenance plan of type p oil tank a, $B_{MTt,p,a}=1$; otherwise $B_{MTt,p,a}=0$

of transportation modes. In such a dynamic, large, and complex scheduling system, current solutions are primarily based on the subjectivity and experience of engineers. Thus, the schedule may not be comprehensively optimal and may result in energy waste and increased operation cost in depot management and export. Recently, the development of computer technology and mathematical optimization has made it possible to develop energy-efficient COPD schedules. Even though oil depot scheduling problems have been investigated, oil depots are merely considered tanks, without regard to detailed operations and their economic effect on the entire system. Aiming at three types of operations processes—receiving, switching, and export transporting—this study establishes a mixed-integer linear programming (MILP) model considering the dynamical variety in the COPD scheduling system, codes an optimal solution program and finally constructs a detailed COPD scheduling model. This model can provide a more objective basis for improving management in the depot system, shortening decision-making time, and reducing energy waste and operation cost.

1.2. *Related work*

The expression of time is the basis of establishing a scheduling model and has a direct effect on the model scale and the selection of the optimization algorithm. Currently, the modeling of time in scheduling models is mainly divided into discrete-time representations (such as Saharidis et al. (2009) and Zhang et al. (2017b)) and continuous-time representations (such as Castro and Grossmann (2014), Lin et al. (2003), Li et al. (2012a), Yadav and Shaik (2012), Reddy et al. (2004a), and Huang and Karimi (2006)).

As detailed COPD scheduling is a complex problem, to simplify the coupling relationship between the model variables, detailed schedules were obtained by methods based on discrete-time representations in previous studies. Discrete-time representations scale well when longer time horizons are required because larger time intervals can be utilized and can easily handle time-varying process conditions (Kelly and Mann, 2003). Shah (1996) developed a discrete-time MILP model for crude oil scheduling by separating it into two sub-problems. The upstream problem comprised portside tanks and offloading, and the downstream problem comprised allocation of charging tanks and operation of crude oil distillation units. Reddy et al. (2004b) proposed a new mixed-integer nonlinear programming (MINLP) formulation based on a discrete-time representation and a novel MILP-based solution approach to optimizing crude oil unloading, storage, and processing operations in a multi-crude distillation unit refinery receiving crude oil from large carriers. Méndez et al. (2006) developed an MILP optimization model for the off-line gasoline blending and short-term scheduling of oil refineries, which could be solved by using an iterative procedure. The objective was to produce on-spec blends at minimum cost subject to stringent and constantly changing product specifications in most markets. Yüzgeç et al. (2010) put forward a model predictive control strategy aiming at minimizing the total operation cost for the short-term refinery scheduling problem. This approach could rapidly determine the optimal control decisions in the presence of disturbances or demand variations at any point over the scheduling horizon. Kelly et al. (2017b) proposed a discrete-time formulation for crude oil blend scheduling optimization and decomposed it into a logistic model and a quality problem.

Compared with the discrete-time representation, the continuous-time representation involves fewer time intervals, reducing the scale of the model to a certain extent (Patel et al., 2010). Pinto et al. (2000) resolved planning and scheduling issues for refinery operations by formulating large-scale MIP optimization models, and discrete- and continuous-time representations were respectively applied for handling these problems. The continuous-time model was found to be able to circumvent the difficulty caused by the relevant difference in the processing time of some operations. Jia et al. (2003) developed a model based on a continuous-time representation, resulting in an MILP and state-task network representation that was used throughout the model. Jia and Ierapetritou (2004) applied event-based multiple time-grid continuous-time models to the crude oil scheduling problem. However, the presence of nonlinear terms in continuous-time models required more appropriate algorithms. Moro and Pinto (2004) aimed at minimizing the depot operation cost and constructed a continuous-time model to reduce volatility in oil quantity and quality in refinery depots. Mouret et al. (2009) proposed a continuous-time formulation, called the single-operation sequencing model, to solve a crude oil operation problem in refineries. Cao et al. (2010) developed stochastic chance-constrained MINLP models for the short-term refinery crude oil scheduling problem in which the objective was the minimization of the operation cost of the depot. Pan et al. (2009) proposed a new MINLP formulation for crude oil scheduling as well as heuristic rules for linearizing the bilinear constraints and selectively prefixing certain binary variables. The crude oil scheduling problem was thus reformulated as a MILP problem with fewer binary variables, which avoids composition discrepancy and affords more effective solutions. Zou et al. (2010) established a continuous-time model based on an event-tree method for operation optimization in long-term scheduling. Event triggered rules, a decomposition strategy, a depth-first search algorithm, and a pruning strategy were adopted to improve the speed of optimal solution search. Li et al. (2012b) considered a crude oil scheduling problem for a typical marine-access refinery under demand uncertainty. They developed a robust optimization model by combining a unit-specific event-based continuous-time formulation with a robust optimization framework. Chen et al. (2012) compared the event-based model, the unit slot model, and the multi-operation sequence (MOS) model, and demonstrated that the MOS model solved the problem considerably faster than the other two models. Capón-García et al. (2013) proposed a rigorous mixed-integer dynamic optimization method for integrating the process dynamics of batch process scheduling. Oliveira et al. (2016) proposed a framework comprising a stochastic optimization model based on MILP for scheduling a crude oil pipeline connecting a marine terminal to an oil refinery and a method for representing oil supply uncertainty. Based on a priority-slot modeling method, Zhao et al. (2016) proposed a continuous-time MINLP formulation for a crude oil scheduling problem considering composition concentration discrepancy. Hou et al. (2017) developed a genetic algorithm (GA) approach for the detailed scheduling problem of crude oil operations in a refinery. An industrial case study was used to show the application of the proposed method.

These studies have addressed the optimization of receiving and export operations of refinery depots; however, special conditions such as switching and maintenance have not yet been considered. Moreover, large regional crude oil scheduling and operation cover wide fields, various study objectives, and relatively large systems. The present study focuses on crude oil systems including offshore oil tankers or barges, port depots, refineries, and pipelines, thus providing a macroscopic perspective. Little research has been conducted on combined transportation modes from port depots to refineries, and the integral optimization of detailed export transport scheduling and operation planning has not been solved effectively.

1.3. *Contributions of this study*

- A mixed-time MILP model is proposed aiming at optimal scheduling of a COPD.
- In this model, the depot system and refinery-oriented supply chain are considered an integrated system.
- Multiple transportation modes, namely pipelines, roads, and railways, are considered.
- Three types of operations processes—oil receiving, valve switching, and oil export—are considered.
- The detailed schedule of a COPD can be obtained.

1.4. *Paper organization*

The methodology and details of the mathematical model are presented in Sections 2 and 3, respectively. Section 4 presents a case study in China. The conclusions are provided in Section 5.

2. 2. Methodology

2.1. *Problem description*

The operation of a COPD is illustrated in Fig. 1. The COPD irregularly receives crude oil of varying quality from different districts. The oil is delivered and stored in tanks. Based on different refinery demands and transportation conditions, an export plan is developed to cater to the downstream market. As the receiving plan and export plan are not synchronized, the target tank should be selected so as to ensure timely and optimal operation. Suboptimal internal storage will lead to poor tank scheduling and considerable berthing and transportation costs. Moreover, in the maintenance period, the oil in the tank under maintenance should be switched into another tank. Otherwise, the switching operation will occur when the oil in the two tanks should be merged for centralized management. Designing a sensible and efficient switching plan will effectively curtail tank operation, expedite tank group maintenance, unify unfilled tanks, and reduce operation cost. According to downstream refinery requirements and

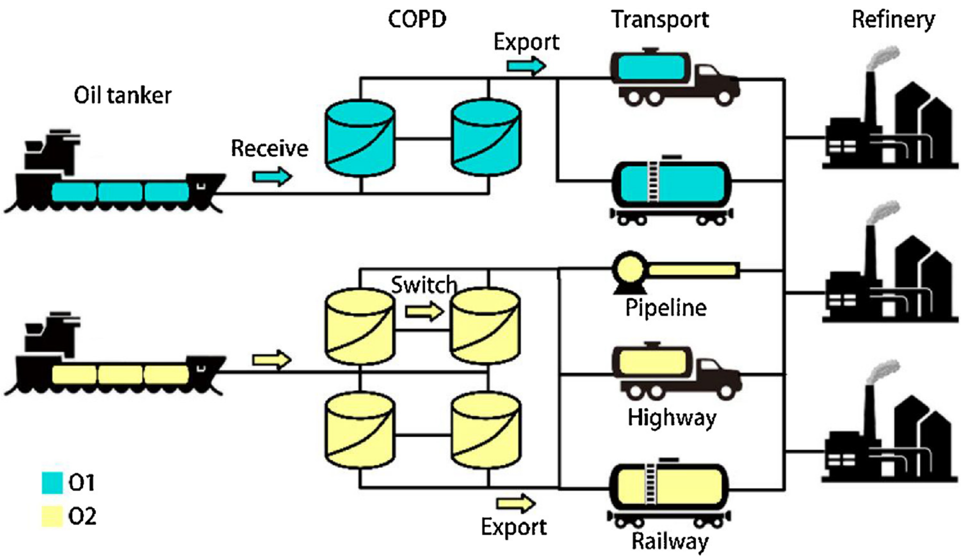


Fig. 1 – COPD operation.

oil characteristics, oil is transported to refineries by certain means. In general, there are three major transportation modes in the refinery supply chain: by pipelines, by rail, and by road.

As pipelines are economical, a large proportion of crude oil is transported through pipelines from depots to refineries on the mainland for refining and delivery to the downstream market. However, in view of practicability issues and terrain difficulties, a large number of refineries cannot be connected via pipelines. In addition, owing to the high initial investment cost and longer investment recovery cycle, some companies cannot afford the high cost of pipeline construction at an early stage.

Railway transportation has lower initial investment cost than pipelines and is characterized by high capacity and safety. However, as a result of higher unit transportation cost, it is only suitable for refineries that are already situated alongside railways and can benefit from this location advantage.

Highway transportation has the major advantages of higher flexibility, shorter construction time, and lower investment cost; moreover, it is easier to adapt to local conditions. Therefore, it is less demanding for the receiving station devices. However, owing to safety issues and the higher cost for long distance carriage, highway transportation is used for refineries that are close to depot areas or unsuitable for pipeline or railway construction. In addition, the oil consumption of refineries restricts the transportation mode. In general, small refineries lack the capital for constructing pipelines or railways; thus, they can choose highway transportation only.

Therefore, refineries that are unreachable by pipelines should be supplied based on local features and take full advantage of other nearby transportation resources. From the perspective of the economy of downstream refineries, a pipeline-oriented, railway and highway backup crude oil supply system is founded, contributing to the variety and complexity of depot oil delivery modes.

Moreover, pipeline transportation has a requirement for higher oil fluidity than highway and railway transportation. As a consequence of various incoming oil types, distinct oil characteristics, and diverse oil fluidity, different types of oil correspond to different conditions of pipeline transportation. For example, light oil has better fluidity. In pipeline transportation, light oil can be delivered to the refinery smoothly without heating or additives such as pour point reducers or viscosity reducers; thus, transportation cost is lower. For heavy oil, which has poor fluidity, heat or additives are required to improve flow characteristics and ensure pipeline transportation safety. This will inevitably increase unit transportation cost and thereby the overall schedule cost. For extra heavy or high pour point crude oil, pipeline transportation may not be possible. As the export cost varies greatly according to oil type, the economic effect of transportation modes should be considered in COPD scheduling.

2.2. *Model requirements*

The model is formulated as an MILP model and is solved using the Gurobi optimization mathematical programming solver. The output of the model is a detailed COPD schedule.

Inputs:

- Study period: start and end time.
- Cost information: unit transportation cost, operation cost, and berthing cost.
- Depot information: oil type, number of tanks, tank storage capacity, and delivery flow capacity.
- Refinery information: oil type demand, volume demand, time period, and transportation mode requirements.
- Oil tanker information: tanker arrival time, oil types carried, and carry volume.
- Tank maintenance information: time period of the maintenance plan.

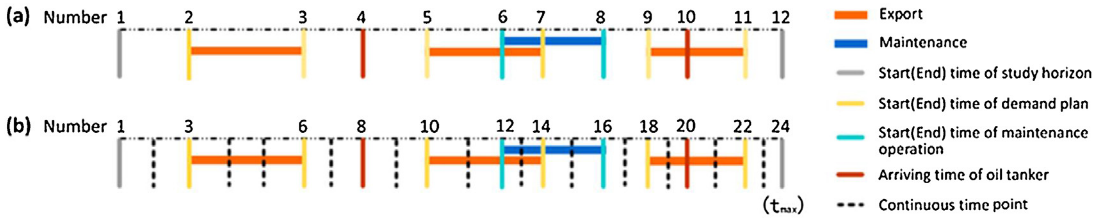


Fig. 2 – Mixed time representation.

To be determined:

- Export plan: export time for each tank, export volume, transportation mode, and export destination.
- Receiving plan: receiving time period for each oil tank and receiving volume.
- Switching plan: switching time period for each oil tank and switching volume.
- Inventory variation of each tank.

Objective:

Minimization of the total operation cost for COPD scheduling under various operational and technical constraints. The total operation cost comprises transportation cost, operation cost for tanks, and berthing cost for oil tankers.

Normally, the duration of oil transportation is taken into account by the demand plan of the refinery. Therefore, the transportation time in each delivery method is not considered in this study.

3. Mathematical formulation

3.1. *Time windows*

Based on a mixed-time representation, this study proposes an MILP model for optimal detailed COPD scheduling. As the schedule for tanker arrival, refinery demand, and maintenance is given during the COPD schedule development, the timing of those events divides the study period into a large number of non-isometric time windows, as shown in Fig. 2(a). However, in several cases, the number of fixed time windows is insufficient. For example, in a time window, each tank can perform only one operation. If the fixed time window is overly long, the total delivery volume may exceed the capacity of the tank. Thus, a contradiction between the model constraints will arise, leading to a non-solution condition. To handle this, several continuous time points are inserted into each fixed time window to divide large discrete intervals into smaller continuous parts, as shown in Fig. 2(b). Multiple operations can thereby be performed in the original large time windows, and the flexibility of the overall schedule is increased. In this process, the time points (both fixed and continuous) are ordered and renumbered as $t = 1, 2, 3, \ldots, t_{max}$. Therefore, the mixed-time representation structure contains the known fixed and the unknown continuous time points, and each operation can be started and finished only at those points. Moreover, as their sequence is known, the order of the fixed time points will constrain the values of the operation state variables. For example, in the maintenance interval (the time windows between the maintenance start time and end time), all operation state variables must be 0 (1 is performing state and 0 is ideal state).

3.2. *Objective function*

To minimize the operation cost F, an MILP model is established. The objective function is min $F = f_1 + f_2 + f_3$. The total operation cost comprises transportation cost f_1, operation cost of tanks f_2, and berthing cost of oil tankers f_3.

The transportation cost is primarily a function of export volume, distance, and transportation mode. It is expressed as follows:

$$f_1 = \sum_t \sum_i \sum_k \sum_p C_{TRi,k,p} L_{i,k} \sum_t V_{OUEi,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{1}$$

The operation cost of tanks is mainly related to the operation time and includes oil receiving, valve switching, and oil export. The total cost is expressed as follows:

$$f_2 = C_{DS} \sum_t \sum_p \sum_a (B_{SEXt,p,a} + 2B_{SSWt,p,a} + B_{SINt,p,a}) \quad t \in T, p \in P, a \in A_p \tag{2}$$

The berthing cost of oil tankers corresponds to the harboring time and is expressed as follows:

$$f_3 = C_{TF} \sum_p \sum_n \tau_{DEMtm,p,n} \quad t \in T, p \in P, a \in A_p \tag{3}$$

3.3. Depot operation constraints

In a certain time window, each tank can have at most one type of operation; when oil is exported, only one transportation mode can be selected. Furthermore, a tank cannot simultaneously switch oil into several other tanks. This is expressed as follows:

$$\sum_i \sum_k B_{EXt,i,k,p,a} + \sum_{a'} B_{SWt,p,a,a'} + \sum_{a'} B_{SWt,p,a',a} + \sum_n B_{INt,p,n,a} \le 1 \quad t \in T, i \in I, k \in K, p \in P, n \in N_p, a, a' \in A_p \tag{4}$$

In a certain time window, several oil tanks cannot export oil to a refinery using the same transportation mode, that is,

$$\sum_a B_{EXt,i,k,p,a} \le 1 \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{5}$$

Owing to the equipment capacity of the COPD, only one type of oil can be received by a tank in a time window, namely,

$$\sum_p \sum_a B_{INt,p,n,a} \le 1 \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{6}$$

According to the definition of the binary variable for the export operation, $B_{SEXt+1,p,a} = 1$ if and only if $\sum_i \sum_k B_{EXt+1,i,k,p,a} = 1$ and $\sum_i \sum_k B_{EXt,i,k,p,a} = 0$; otherwise, $B_{SEXt+1,p,a} = 0$. The specific logical relationship is expressed as follows:

$$B_{SEXt+1,p,a} \le \sum_i \sum_k B_{EXt+1,i,k,p,a} + \sum_i \sum_k B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{7}$$

$$B_{SEXt+1,p,a} \ge \sum_i \sum_k B_{EXt+1,i,k,p,a} - \sum_i \sum_k B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{8}$$

$$B_{SEXt+1,p,a} \le 1 - \sum_i \sum_k B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{9}$$

The binary variables for the switching operation have the same logic as that for the export operation:

$$B_{SSWt+1,p,a} \le \sum_{a'} B_{SWt+1,p,a',a} + \sum_{a'} B_{SWt,p,a',a} \quad t \in T, p \in P, a, a' \in A_p \tag{10}$$

$$B_{SSW_{t+1,p,a}} \ge \sum_{a'} B_{SW_{t+1,p,a',a}} - \sum_{a'} B_{SW_{t,p,a',a}} \quad t \in T, p \in P, a, a' \in A_p \tag{11}$$

$$B_{SSWt+1,p,a} \le 1 - \sum_{a'} B_{SW_{t,p,a',a}} \quad t \in T, p \in P, a, a' \in A_p \tag{12}$$

with the constraints for the binary variables for the receiving operation, i.e.,

$$B_{SINt+1,p,n,a} \le B_{INt+1,p,n,a} + B_{INt,p,n,a} \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{13}$$

$$B_{SINt+1,p,n,a} \ge B_{INt+1,p,n,a} - B_{INt,p,n,a} \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{14}$$

$$B_{SINt+1,p,n,a} \le 1 - B_{INt,p,n,a} \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{15}$$

and those for the binary variables for the transport initiation, i.e.,

$$B_{AEXt+1,i,k,p} \le \sum_a B_{EXt+1,i,k,p,a} + \sum_a B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{16}$$

$$B_{AEXt+1,i,k,p} \ge \sum_a B_{EXt+1,i,k,p,a} - \sum_a B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{17}$$

$$B_{AEXt+1,i,k,p} \le 1 - \sum_a B_{EXt,i,k,p,a} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{18}$$

being expressed in a similar manner.

The start time of each time window must be earlier than that of the next time window, namely,

$$\tau_t \le \tau_{t+1} \quad t \in T \tag{19}$$

3.4. *Tank inventory constraints*

Herein, M represents a sufficiently large positive value. When the binary variables for the export operation are zero, the corresponding export volume must be zero, that is,

$$B_{\mathrm{EX}t,i,k,p,a} M \ge V_{\mathrm{OUE}t,i,k,p,a}, \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{20}$$

When the binary variables for the switching operation are zero, the corresponding switching volume must be zero, i.e.,

$$B_{\mathrm{SW}t,p,a,a'} M \ge V_{\mathrm{OUS}t,p,a,a'} \quad t \in T, p \in P, a, a' \in A_p \tag{21}$$

When the binary variables for the receiving operation are zero, the corresponding receiving volume must be zero, namely,

$$B_{\mathrm{IN}t,p,n,a} M \ge V_{\mathrm{ADI}t,p,n,a}, \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{22}$$

With volume conservation, the tank storage volume at the start of each time window should be equal to the storage volume at the start of the previous time window minus the export volume and switched volume, with the addition of the receiving volume and the switched oil volume from other storage tanks. That is,

$$V_{\mathrm{TIN}t+1,p,a} = V_{\mathrm{TIN}t,p,a} - \sum_i \sum_k V_{\mathrm{OUE}t,i,k,p,a} - \sum_{a'} V_{\mathrm{OUS}t,p,a,a'} + \sum_{a'} V_{\mathrm{OUS}t,p,a',a} + \sum_n V_{\mathrm{ADI}t,p,n,a} \quad t \in T, i \in I, k \in K, p \in P, n \in N_p, a, a' \in A_p \tag{23}$$

The inventory should be less than the maximum storage capacity, i.e.,

$$V_{\mathrm{TIN}t,p,a} \le V_{\mathrm{Tmax}p,a} \quad t \in T, p \in P, a \in A_p \tag{24}$$

If maintenance is required, the minimal storage volume should be set to zero, namely,

$$V_{\mathrm{TIN}t,p,a} \ge V_{\mathrm{Tmin}p,a} - B_{\mathrm{MT}t,p,a} M \quad t \in T, p \in P, a \in A_p \tag{25}$$

$$V_{\mathrm{TIN}t,p,a} \le B_{\mathrm{MT}t,p,a} M, \quad t \in T, p \in P, a \in A_p \tag{26}$$

3.5. *Export constraints*

One time window should start with the export plan, i.e., $\sum_t B_{\mathrm{TEXB}t,i,p,z} = 1$, and $\tau_t = \tau_{\mathrm{EXB}p,i,z}$ only when $B_{\mathrm{TEXB}t,i,p,z} = 1$, namely,

$$\tau_t \le \tau_{\mathrm{EXB}p,i,z} + (1 - B_{\mathrm{TEXB}t,i,p,z}) M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{27}$$

$$\tau_t \ge \tau_{\mathrm{EXB}i,p,z} + (B_{\mathrm{TEXB}t,i,p,z} - 1) M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{28}$$

$$\sum_t B_{\mathrm{TEXB}t,i,p,z} = 1 \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{29}$$

The logical relations of the variable constraints at the end time of the export plan are the same as those at the start time, that is,

$$\tau_t \le \tau_{\mathrm{EXN}i,p,z} + (1 - B_{\mathrm{TEXN}t,i,p,z}) M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{30}$$

$$\tau_t \ge \tau_{\mathrm{EXN}i,p,z} + (B_{\mathrm{TEXN}t,i,p,z} - 1) M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{31}$$

$$\sum_t B_{\mathrm{TEXN}t,i,p,z} = 1 \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{32}$$

According to the definition of the binary variables for the export requirements, during the export period, $B_{\mathrm{EXM}t,i,p,z} = 1$, i.e.,

$$B_{\mathrm{EXM}t+1,i,p,z} = B_{\mathrm{EXM}t,i,p,z} + B_{\mathrm{EXB}t+1,i,p,z} - B_{\mathrm{EXN}t+1,i,p,z} \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{33}$$

If the binary variables for the export requirements are zero, the export operation is forbidden, namely,

$$\sum_{z} B_{EXMt,i,p,z} M \geq \sum_{k}\sum_{a} B_{EXt,i,k,p,a} \quad t \in T, k \in K, i \in I, p \in P, a \in A_p, z \in Z_{i,p} \tag{34}$$

If the binary variables for the export requirements are equal to 1, the accumulated export volume is equal to the export volume of the previous time window plus the volume during the previous time window, that is,

$$V_{EXACt+1,i,p,z} \leq V_{EXACt,i,p,z} + \sum_{k}\sum_{a} V_{OUEt,i,k,p,a} + (1 - B_{EXMt,i,p,z})M \quad t \in T, k \in K, i \in I, p \in P, a \in A_p, z \in Z_{i,p} \tag{32}$$

$$V_{EXACt+1,i,p,z} \geq V_{EXACt,i,p,z} + \sum_{k}\sum_{a} V_{OUEt,i,k,p,a} + (B_{EXMt,i,p,z} - 1)M \quad t \in T, k \in K, i \in I, p \in P, a \in A_p, z \in Z_{i,p} \tag{35}$$

If the binary variables for the export requirements are zero, then the accumulated export volume is equal to the export volume started in the previous time window, i.e.,

$$V_{EXACt+1,i,p,z} \leq V_{EXACt,i,p,z} + B_{EXMt,i,p,z} M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{36}$$

$$V_{EXACt+1,i,p,z} \geq V_{EXACt,i,p,z} - B_{EXMt,i,p,z} M \quad t \in T, i \in I, p \in P, z \in Z_{i,p} \tag{37}$$

The final accumulated export volume is equal to the required export volume, namely,

$$V_{EXACtm,i,p,z} = V_{DEMAi,p,z} \quad i \in I, p \in P, z \in Z_{i,p} \tag{38}$$

The export flow should satisfy the following flow constraints:

$$\sum_{a} V_{OUEt,i,k,p,a} \leq (\tau_{t+1} - \tau_t) Q_{EOmaxk,p} + \sum_{p'} B_{MIXTRt,p,p'} M + (1 - \sum_{a} B_{EXt,i,k,p,a})M \quad t \in T, i \in I, k \in K, p, p' \in P, a \in A_p \tag{39}$$

$$\sum_{a} V_{OUEt,i,k,p,a} \geq (\tau_{t+1} - \tau_t) Q_{EOmink,p} - \sum_{p'} B_{MIXTRt,p,p'} M + (\sum_{a} B_{EXt,i,k,p,a} - 1)M \quad t \in T, i \in I, k \in K, p, p' \in P, a \in A_p \tag{40}$$

By considering the features of railway and highway transportation, the export volume should be an integral multiple of the unit capacity volume of the transportation equipment, and the multiplicative factor is the number of pieces of transportation equipment, which should be smaller than the maximum available number. That is,

$$\sum_{a} V_{OUEt,i,k,p,a} = V_{UVKk} N_{Kt,i,k,p} \quad t \in T, i \in I, k \in K, p \in P, a \in A_p \tag{41}$$

$$\sum_{t}\sum_{i}\sum_{p} N_{Kt,i,k,p} \leq N_{Kmaxk} \quad t \in T, i \in I, k \in K, p \in P \tag{42}$$

3.6. *Receiving constraints*

The start of a time window must coincide with the beginning of the oil receiving operation, which implies that $\sum_{t} B_{TDEBt,p,n}$ must be equal to 1, and $\tau_t = \tau_{DEBp,n}$ only when $B_{TDEBt,p,n} = 1$. Namely,

$$\tau_t \leq \tau_{DEBp,n} + (1 - B_{TDEBt,p,n})M \quad t \in T, p \in P, n \in N_p \tag{43}$$

$$\tau_t \geq \tau_{DEBp,n} + (B_{TDEBt,p,n} - 1)M \quad t \in T, p \in P, n \in N_p \tag{44}$$

$$\sum_{t} B_{TDEBt,p,n} = 1 \quad t \in T, p \in P, n \in N_p \tag{45}$$

The start time of oil receiving is determined by the tanker arrival time, but its end time is determined by the oil receiving plan, which implies that the end time is also a decision variable. Furthermore, one time window should start with the end of oil receiving, which implies that $\sum_{t} B_{TDENt,p,n}$ must be equal to 1, and $\tau_t = \tau_{DENp,n}$ only when $B_{TDENt,p,n} = 1$. That is,

$$\tau_t \leq \tau_{DENp,n} + (1 - B_{TDENt,p,n})M \quad t \in T, p \in P, n \in N_p \tag{46}$$

$$\tau_t \geq \tau_{DENp,n} + (B_{TDENt,p,n} - 1)M \quad t \in T, p \in P, n \in N_p \tag{47}$$

Table 1 – Demand plan of refineries.

Ex.	Re.	Dem. plan z	Venezuela oil			UAE oil		
			St. time (h)	En. time (h)	Dem. volume (m^3)	St. time (h)	En. time (h)	Dem. volume (m^3)
1	1#	1	50	74	16,876	15	39	32,258
		2	220	244	17,384	283	307	31,818
	2#	1	130	154	8344	102	126	20,453
		2	285	309	9434	307	331	19,434
	3#	1	178	202	16,485	78	102	35,646
		2	258	282	16,864	250	274	35,477
2	1#	1	166	190	12,986	192	216	28,145
		2	302	326	12,465	400	424	29,245
		3	499	523	12,464	611	635	28,496
		4	664	688	12,917	-	-	-
	2#	1	79	103	13,080	32	56	31,029
		2	259	283	13,167	215	239	31,629
		3	439	463	13,463	448	472	29,864
	3#	1	21	45	14,867	105	129	29,587
		2	191	215	14,466	308	332	29,343
		3	361	385	15,461	490	514	29,364
		4	531	555	15,617	646	670	30,415
3	1#	1	101	125	13,435	41	65	32,968
		2	281	305	12,948	306	330	33,216
		3	469	493	13,154	611	635	33,179
		4	660	684	13,867	–	–	–
	2#	1	159	183	14,345	69	93	34,684
		2	425	449	13,969	374	398	33,948
		3	635	659	14,138	585	609	34,165
	3#	1	131	155	13,284	12	36	26,268
		2	321	345	14,466	178	202	26,324
		3	501	525	15,461	399	423	26,177
		4	687	711	15,617	537	561	27,157

Ex.: example number. Re.: refinery number. Dem. plan: demand plan number. St. time: start time of the plan. En. time: end time of the plan. Dem. volume: demand volume.

$$\sum_t B_{TDENt,p,n} = 1 \quad t \in T, p \in P, n \in N_p \tag{48}$$

The end time of oil receiving must be later than the start time, i.e.,

$$\tau_{DENp,n} \geq \tau_{DEBp,n} \quad p \in P, n \in N_p \tag{49}$$

As in the definition of the binary variables for the receiving requirements, during oil delivery, $B_{DEMt,p,n} = 1$, that is,

$$B_{DEMt+1,p,n} = B_{DEMt,p,n} + B_{DEBt+1,p,n} - B_{DENt+1,p,n} \quad t \in T, p \in P, n \in N_p \tag{50}$$

If the binary variables for the receiving requirements are zero, the binary variables for the receiving operation must be zero, namely,

$$\sum_n B_{DEMt,p,n} M \geq \sum_a B_{INt,p,n,a} \quad t \in T, k \in K, p \in P, n \in N_p, a \in A_p \tag{51}$$

If the binary variables for the receiving requirements are equal to 1, then the accumulated receiving oil volume is equal to the accumulated receiving oil at the start time of the previous time window plus the receiving volume during the previous time window. That is,

$$V_{DEACt+1,p,n} \leq V_{DEACt,p,n} + \sum_a V_{ADIt,p,n,a} + (1 - B_{DEMt,p,n})M \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{52}$$

$$V_{DEACt+1,p,n} \geq V_{DEACt,p,n} + \sum_a V_{ADIt,p,n,a} + (B_{DEMt,p,n} - 1)M \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{53}$$

Table 2 – Receiving plan of the COPD.

Ex.	Rec. plan n	Venezuela oil		UAE oil	
		St. time (h)	Rec. volume ($\times 10^6$ m^3)	St. time (h)	Rec. volume ($\times 10^6$ m^3)
1	1	200	15	280	15
2	1	650	15	340	15
	2	–	–	720	15
3	1	680	15	493	15
	2	–	–	710	15

Rec. plan: receiving plan number. Dem. volume: demand volume.

Table 3 – Computation results.

Ex.	Cont. var.	Disc. var.	# of eq. con.	# of ineq. con.	f_1 ($\times 10^3$ CNY)	f_2 ($\times 10^3$ CNY)	f_3 ($\times 10^3$ CNY)	F ($\times 10^3$ CNY)	CPU time (s)	Gap	CPU time of PCE (s)
1	5730	8832	39,521	1262	2851,1	1.5	498.5	3081.1	235	0.02%	318
2	9999	16,218	69,571	2514	5017.5	3.4	498.5	5519.4	475	0.03%	554
3	9607	15,582	66,976	2418	5261.1	3.4	498.5	5763.0	329	0.06%	435

Cont. var.: number of continuous variables. Disc. var.: number of discrete variables. Par.: number of parameters. # ofeq. con.: number of equality constraints. # ofineq. con.: number of inequality constraints. PCE: parallel computing experiment.

If the binary variables of the receiving requirements are zero, then the accumulated receiving oil is equal to the accumulated receiving oil at the start time of the previous time window, i.e.,

$$V_{\mathrm{DEAC}t+1,p,n} \le V_{\mathrm{DEAC}t,p,n} + B_{\mathrm{DEM}t,p,n}M \quad t \in T, p \in P, n \in N_p \tag{54}$$

$$V_{\mathrm{DEAC}t+1,p,n} \ge V_{\mathrm{DEAC}t,p,n} - B_{\mathrm{DEM}t,p,n}M \quad t \in T, p \in P, n \in N_p \tag{55}$$

The final accumulated receiving oil volume should be equal to the carry volume of the tanker, namely,

$$V_{\mathrm{DEAC}tm,p,n} = V_{\mathrm{SHMA}p,n} \quad t \in T, p \in P, n \in N_p \tag{56}$$

If the binary variables for oil receiving are equal to 1, then the accumulated harboring time is equal to the accumulated harboring time at the start of the previous time window plus the time step of the previous time window. That is,

$$\tau_{\mathrm{DEM}t+1,p,n} \le \tau_{\mathrm{DEM}t,p,n} + \tau_{t+1} - \tau_t + (1 - B_{\mathrm{DEM}t,p,n})M \quad t \in T, p \in P, n \in N_p \tag{57}$$

$$\tau_{\mathrm{DEM}t+1,p,n} \ge \tau_{\mathrm{DEM}t,p,n} + \tau_{t+1} - \tau_t + (B_{\mathrm{DEM}t,p,n} - 1)M \quad t \in T, p \in P, n \in N_p \tag{58}$$

If the binary variables of oil receiving are zero, then the accumulated harboring time is equal to the accumulated harboring time started in the previous time window, i. e.,

$$\tau_{\mathrm{DEM}t+1,p,n} \le \tau_{\mathrm{DEM}t,p,n} + B_{\mathrm{DEM}t,p,n}M \quad t \in T, p \in P, n \in N_p \tag{59}$$

$$\tau_{\mathrm{DEM}t+1,p,n} \ge \tau_{\mathrm{DEM}t,p,n} - B_{\mathrm{DEM}t,p,n}M \quad t \in T, p \in P, n \in N_p \tag{60}$$

Receiving flow must satisfy the following flow limit constraints:

$$\sum_a V_{\mathrm{ADI}t,p,n,a} \le (\tau_{t+1} - \tau_t)Q_{\mathrm{DOmax}p} + (1 - \sum_a B_{\mathrm{IN}t,p,n,a})M \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{61}$$

$$\sum_a V_{\mathrm{ADI}t,p,n,a} \ge (\tau_{t+1} - \tau_t)Q_{\mathrm{DOmin}p} + (\sum_a B_{\mathrm{IN}t,p,n,a} - 1)M \quad t \in T, p \in P, n \in N_p, a \in A_p \tag{62}$$

3.7. *Maintenance constraints*

If storage tanks require maintenance, one time window should start with the maintenance. That is, $\sum_t B_{\mathrm{TMDB}t,p,a}$ must be equal to 1, and $\tau_t = \tau_{\mathrm{MDB}p,a}$ only when $B_{\mathrm{TMDB}t,p,a} = 1$. Namely,

$$\tau_t \le \tau_{\mathrm{MDB}p,a} + (1 - B_{\mathrm{TMDB}t,p,a})M \quad t \in T, p \in P, a \in A_p \tag{63}$$

$$\tau_t \ge \tau_{\mathrm{MDB}p,a} + (B_{\mathrm{TMDB}t,p,a} - 1)M \quad t \in T, p \in P, a \in A_p \tag{64}$$

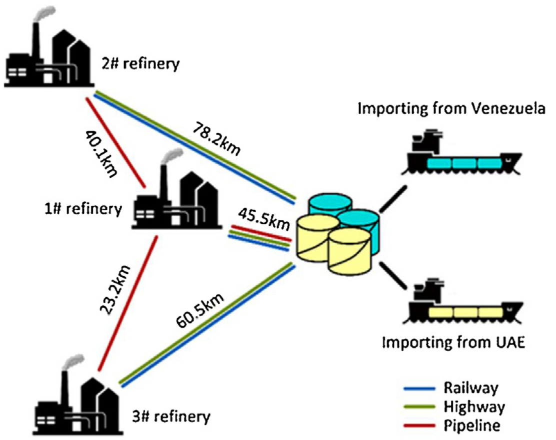


Fig. 3 – Supply and market chain of Qingdao COPD.

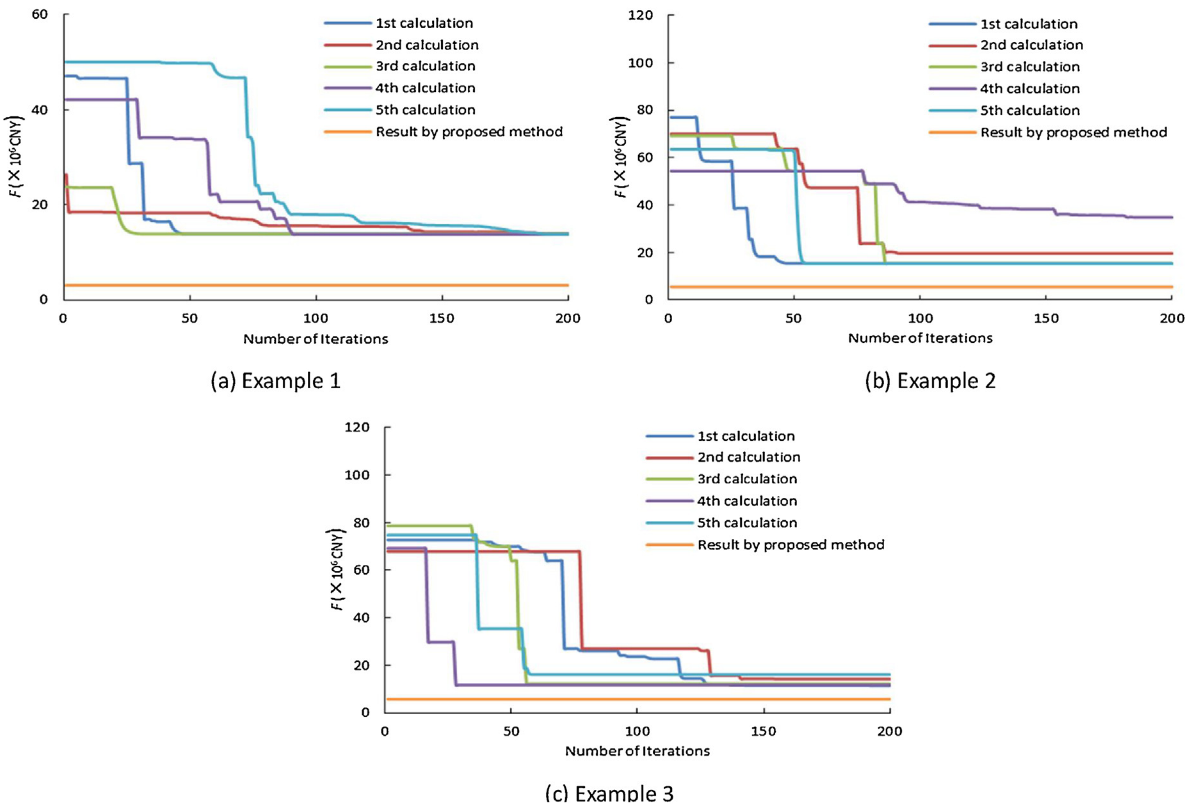


Fig. 4 – Computation results of GA.

$$\sum_t B_{\mathrm{TMDB}t,p,a} = 1 \quad t \in T, i \in I, p \in P, a \in A_p \tag{65}$$

If oil tanks require maintenance, the start of one time window must coincide with the end of maintenance work. Thus, $\sum_t B_{\mathrm{TMDN}t,p,a}$ must be equal to 1, and $\tau_t = \tau_{\mathrm{MDN}p,a}$ only when $B_{\mathrm{TMDN}t,p,a} = 1$. That is,

$$\tau_t \le \tau_{\mathrm{MDN}p,a} + (1 - B_{\mathrm{TMDN}t,p,a})M \quad t \in T, p \in P, a \in A_p \tag{66}$$

$$\tau_t \ge \tau_{\mathrm{MDN}p,a} + (B_{\mathrm{TMDN}t,p,a} - 1)M \quad t \in T, p \in P, a \in A_p \tag{67}$$

$$\sum_t B_{\mathrm{TMDN}t,p,a} = 1 \quad t \in T, i \in I, p \in P, a \in A_p \tag{68}$$

According to the binary variables for maintenance conditions, during maintenance, $B_{\mathrm{MT}t,p,a} = 1$. Namely,

$$B_{\mathrm{MT}t+1,p,a} = B_{\mathrm{MT}t,p,a} + B_{\mathrm{MDB}t+1,p,a} - B_{\mathrm{MDN}t+1,p,a} \quad t \in T, p \in P, a \in A_p \tag{69}$$

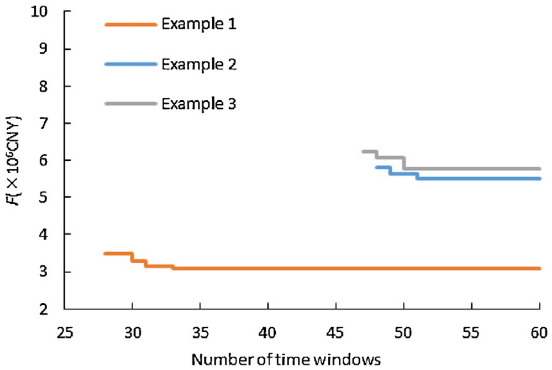


Fig. 5 – Computation results with different numbers of time windows.

4. Results and Discussion

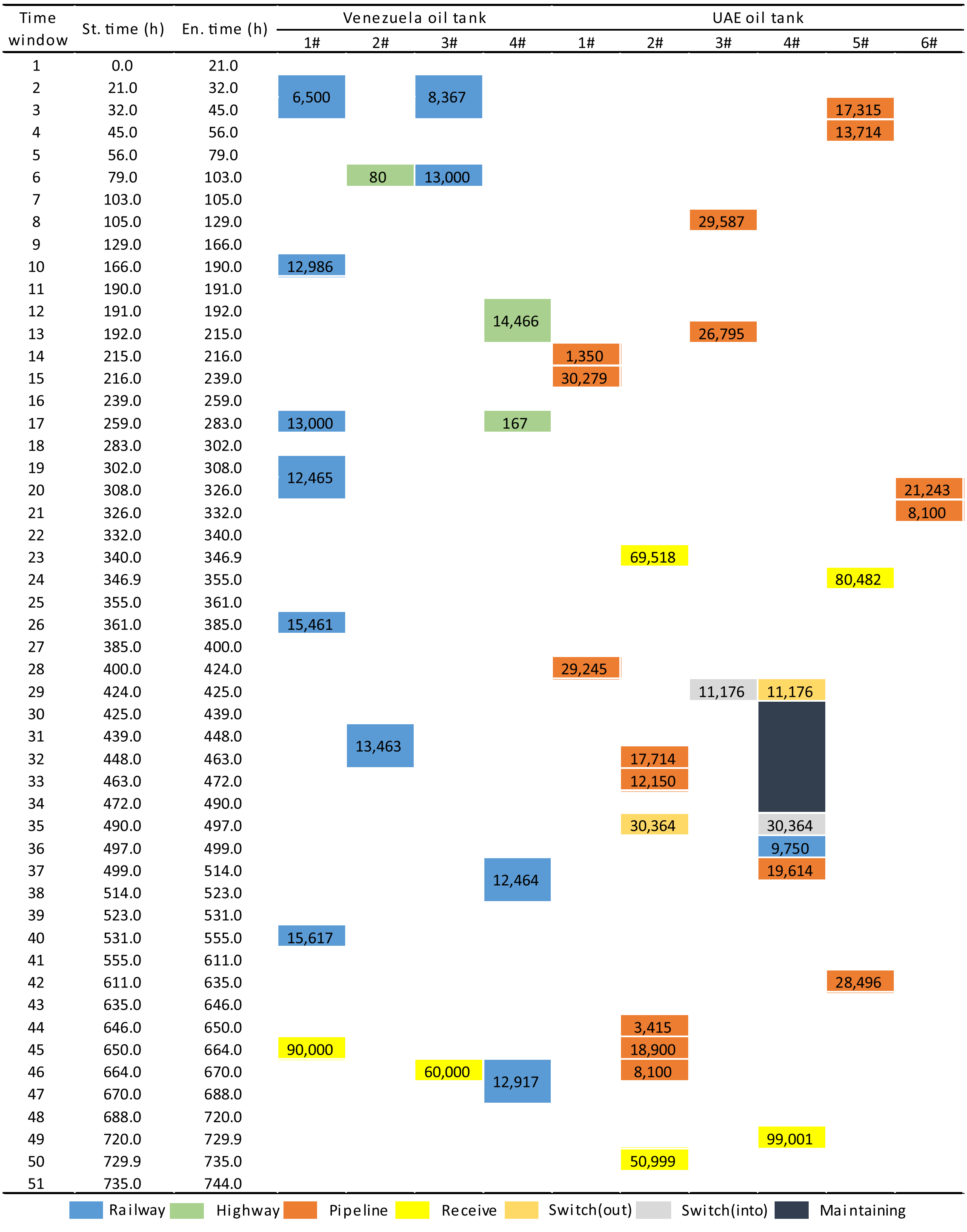
A COPD in China is considered as an example (Fig. 3). This COPD receives crude oil imported from Venezuela, which is heavy and has high viscosity, and the United Arab Emirates (UAE), which has better fluidity. The storage capacity of the COPD is 1,000,000 m^3 with four 100,000 m^3 storage tanks for Venezuelan oil and six 100,000 m^3 storage tanks for UAE oil. The COPD has three refineries (1#, 2#, and 3#) as market terminals; transportation is performed by rail, road, and pipelines. Currently, the most difficult problem of the COPD is that tanks in oil refineries have limited capacity, and thus crude oil must be replenished frequently and periodically. This increases the transport initiation cost owing to repeated shut-down if oil is transported by pipelines. By artificial scheduling, the shortest time period for pipeline transportation is 10 h, with low utilization efficiency and large energy

Time window	St. time (h)	En. time (h)	Venezuela oil tank				UAE oil tank					
			1#	2#	3#	4#	1#	2#	3#	4#	5#	6#
1	0.0	15.0										
2	15.0	39.0						32,258				
3	39.0	50.0										
4	50.0	74.0		16,876								
5	74.0	78.0										
6	78.0	83.9								7,922		
7	83.9	100.0							21,778	3,246		
8	100.0	102.0							2,700			
9	102.0	126.0							20,453			
10	126.0	130.0										
11	130.0	154.0		8,344								
12	154.0	172.0										
13	172.0	178.0										
14	178.0	200.0			16,485							
15	200.0	202.0		20,000								
16	202.0	208.8		68,000								
17	208.8	215.0				62,000						
18	215.0	220.0										
19	220.0	244.0	17,384									
20	244.0	250.0										
21	250.0	258.0									10,800	
22	258.0	274.0									21,600	
23	274.0	280.0		16,864								
24	280.0	282.0							20,000			
25	282.0	283.0							10,000			
26	283.0	285.0							20,000	2,118		
27	285.0	285.3							2,999	405		
28	285.3	295.0								13,042		99,001
29	295.0	302.0			9,434					9,503		
30	302.0	307.0								6,750		
31	307.0	309.0								2,700		
32	309.0	331.0								16,734		
33	331.0	336.0										

Railway Highway Pipeline Receive Switch(out) Switch(into) Maintaining

(a) Example 1

Fig. 6 – Detailed COPD schedule.



(b) Example 2

Fig. 6 – (*Continued*)

consumption. Moreover, with regard to the possibility of congelation after shut-down, pipeline transportation cannot be adopted, owing to the high viscosity and high pour point of Venezuelan oil.

To demonstrate the practicality of the proposed method, three real schedules are taken as examples. The study horizon in Example 1 is two weeks (336 h) and that in the other two examples is one month (744 h). The demand plans of the refineries and the receiving plans of the COPD in each example are listed in Tables 1 and 2. In Example 2, tank 4# for Venezuelan oil will be maintained from 425 to 497 h.

The computation results are listed in Table 3. As a number of related methods have been proposed, GA, a typical global optimal searching algorithm, was used for comparison. The structure of the model was based on Hou et al. (2016), and the additional constraints were programmed into the constraint matrix and used in the MATLAB GA Optimization Tool. The parameters and computational logics of GA were chosen as defaults. To examine the stability of GA, the computation was repeated five times

Time window	St. time (h)	En. time (h)	Venezuela oil tank 1#	Venezuela oil tank 2#	Venezuela oil tank 3#	Venezuela oil tank 4#	UAE oil tank 1#	UAE oil tank 2#	UAE oil tank 3#	UAE oil tank 4#	UAE oil tank 5#	UAE oil tank 6#
1	0.0	12.0										
2	12.0	36.0								26,268		
3	36.0	41.0										
4	41.0	65.0										26,968
5	65.0	69.0										5,400
6	69.0	93.0										32,400
7	93.0	101.0										
8	101.0	125.0		435		13,000						
9	125.0	131.0										
10	131.0	155.0	13,000		284							
11	155.0	159.0										
12	159.0	178.0		14,345								
13	178.0	183.0					6,750					
14	183.0	202.0					19,574					
15	202.0	281.0										
16	281.0	305.0		12,948								
17	305.0	306.0										
18	306.0	321.0					816				20,250	
19	321.0	330.0			14,466		12,150					
20	330.0	345.0										
21	345.0	350.0										
22	350.0	374.0										
23	374.0	398.0					1,548		31,050			
24	398.0	399.0							1,350			
25	399.0	423.0							26,177			
26	423.0	425.0										
27	425.0	449.0	13,000			969						
28	449.0	469.0										
29	469.0	493.0	154			13,000						
30	493.0	501.0						80,000				
31	501.0	508.0			15,461							70,000
32	508.0	525.0										
33	525.0	537.0										
34	537.0	561.0										27,157
35	561.0	585.0										
36	585.0	609.0							1,765			32,400
37	609.0	611.0										
38	611.0	635.0					779	32,400				
39	635.0	659.0	13,000	1,138								
40	659.0	660.0										
41	660.0	680.0	13,000									
42	680.0	684.0	867	40,000								
43	684.0	687.0		30,000								
44	687.0	695.0				80,000						
45	695.0	710.0		15,617								
46	710.0	711.0							10,000			
47	711.0	715.3							42,583			
48	715.3	725.0									97,417	
49	725.0	733.0										
50	733.0	744.0										

Railway Highway Pipeline Receive Switch(out) Switch(into) Maintaining

(c) Example 3

Fig. 6 – *(Continued)*

for each example. The computation results of GA are shown in Fig. 4. Sensitivity analysis for the number of time windows was conducted as shown in Fig. 5. The optimal schedule for each example is shown in Fig. 6.

As shown in Fig. 4, the final result by GA is on average more than three times as high as that of the proposed method. The coefficient of variation in each example is 0.034, 0.3145, and 0.1545, respectively. The coefficient of variation in Example 1 is relatively low but that of Example 2 is sufficiently high to prove the poor stability of GA. This indicates the complexity of the studied target, the large scale of the model, and the complicated logic relations between variables. Moreover, it demonstrates that the proposed method can better handle this type of complex COPD scheduling problem.

As for all tanks, only one operation can be performed in a time window, the number of time windows is crucial to the optimal solution. If this number is insufficient for the required operation, the model will have no solution owing to its contradictory constraints. Furthermore, additional time windows may decrease computation speed instead of improving it. As shown in Fig. 5, there is no solution when the number of time windows is relatively small, whereas when the number of time windows increases

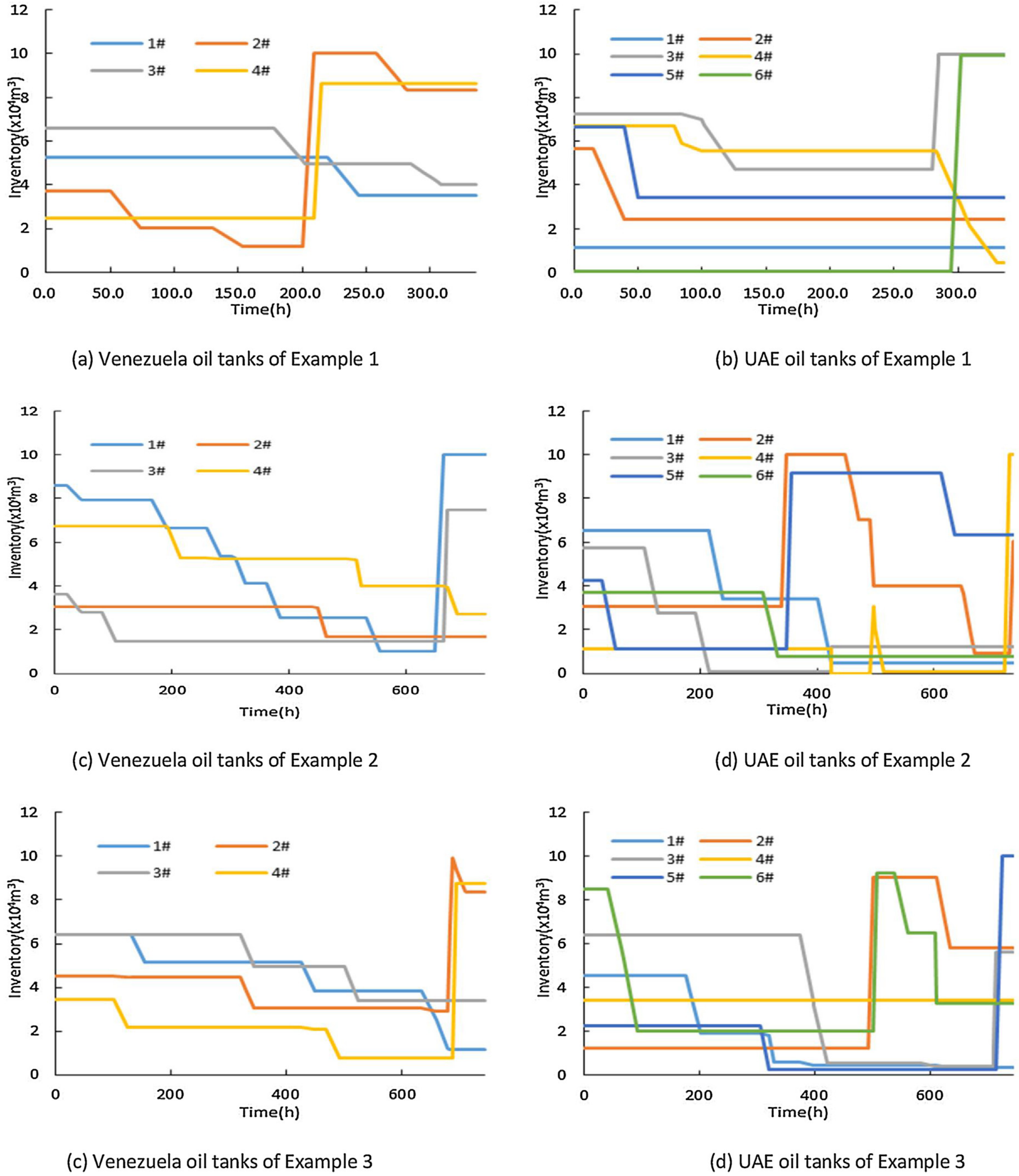


Fig. 7 – Inventory variation of each tank.

to a certain value, there is a solution, and when the number further grows, the solution is optimized and is obviously improved, as shown by the result of Example 2 (48 fixed time points). There is no solution until the number of time windows increases to 48. The optimal result can be obtained when a new time window is added. However, once this number reaches 51, there is no improvement by further increasing the number of time windows. Fig. 6(b) shows the final schedule for Example 2. Four continuous time points are inserted into the study period (346.9, 355, 729.9, and 735 h), and correspondingly four new time windows are added. In these time windows, the depots receive only UAE oil. As the maximum capacity of the tanks is 10×10^6 m^3, a minimum of two receiving operations is required to receive oil from 15×10^6 m^3 tankers. As shown in Fig. 5(b), 15×10^6 m^3 tankers for UAE oil arrive at the COPD at 340 and 720 h. On the second arrival, tank 4# begins to receive oil at the maximum rate to ensure the minimum harboring time until 729.9 h when the tank capacity reaches the upper limit, and then tank 2# begins to receive oil and finishes at 735.0 h. In this case, if the two continuous time points of 729.9 and 735 h are not added, there will be only a fixed time window (720–744 h), resulting in excessively large berthing cost.

As the number of continuous time points is important for model construction, an enumerative method was developed for determining the optimal number of continuous time points. As the optimal solution of the model with fewer continuous time points must be a feasible solution for the model with more continuous time points, the optimal solution should not worsen by increasing the number of continuous time points. Therefore, it suffices to increase the number of time points and repeatedly solve the problem. When the objective function can stably convergence to a value, the number of its continuous time points is the optimal solution. During actual operation, although an approximate feasible range for the number of time windows could be empirically determined, various numbers of time points should examined to obtain the final optimal result, which may be time consuming in some large-scale depot systems. Nevertheless, owing to the independence of the experiments, parallel computing may be used to resolve this. Here, a parallel computing experiment was designed to assess the impact of the optimal time point searching process on total CPU time. Ten instances of the proposed model were simultaneously run, with the number of continuous time points set from one to ten. The CPU time for the three examples is listed in Table 3. The total computation time did not significantly increase, thus demonstrating the practicability of the proposed method.

As shown in Fig. 6, this schedule can meet the requirements of each refinery as well as the unloading plan of oil tankers. Thus, the practicability of the method is confirmed. In addition, this schedule extends the pipeline transportation time as much as possible, ensuring that the pipeline constantly runs more than 24 h, thereby reducing energy cost by repeated transport initiation. The inventory variation of each tank is shown in Fig. 7.

As shown in Fig. 7, the schedule can meet the inventory capacity limit of each tank, thus demonstrating the practicability of the method. In addition, this method takes tank inspection and repair into consideration, so that transit operations can be performed in advance. Under regular operations, the operation time of the COPD tanks should be reduced to the greatest extent. As known from Examples 2 and 3, tanks 4# and 6# of UAE oil are not operated for a considerably long time.

5. Conclusions

A new method for detailed COPD scheduling based on a mixed-time MILP method was proposed. The proposed model considers the issues of multiple transportation modes—namely pipelines, highways, and railways—and multiple operations—namely oil export, oil receiving, and valve switching. These factors not only enhance the practicability but also increase the complexity of the formulation. To minimize the cost of COPD scheduling, the cost of transportation, tank operation, oil tanker harboring as well as the constraints of tank inventory, oil export and receiving, and maintenance were included.

The proposed method was successfully applied to a real-world COPD system in China, which comprises ten tanks and can receive and export two types of crude oil imported from Venezuela and the UAE. The model provided a monthly detailed schedule in three real cases. The results met all constraints and requirements of the field and therefore can be used as a guide for site operation. Compared with GA, the proposed method yielded more accurate results with improved computational stability.

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