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Original Paper

An integrated MINLP model for multi-party coordination in downstream oil supply chain

Rui Qiu [a], Bo Zhang [a], Wei Zhao [a], Ren-Fu Tu [a], Man-Qiu He [b], Qi Liao [a,*], Yong-Tu Liang [a,**]

[a] National Engineering Laboratory for Pipeline Safety/Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum-Beijing, Fuxue Road No.18, Changping District, Beijing, 102249, PR China

[b] Strategy & Implementation Department, PipeChina, Dongtucheng Road No.5, Chaoyang District, Beijing, 100013, PR China

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ABSTRACT

Cooperation among enterprises can bring overall and individual performance improvement, and a smooth coordination method is indispensable. However, due to the lack of customized coordination methods, cooperation in the downstream oil supply chain cannot be carried out smoothly. This paper intends to propose a multi-party coordination method to promote cooperation between oil shippers and pipeline operator by optimizing oil transportation, oil substitution and pipeline pricing schemes. An integrated game-theoretic modeling and analysis approach is developed to characterize the operation behaviors of all stakeholders in the downstream oil supply chain. The proposed mixed integer nonlinear programming model constrains supply and demand capacity, transportation routes, oil substitution rules and pipeline freight levels. Logarithm transformation and price discretization are introduced for model linear approximation. Simulation experiments are carried out in the oil distribution system in South China. The results show that compared to the business-as-usual scheme, the new scheme saves transportation cost by 3.48%, increases pipeline turnover by 5.7%, and reduces energy consumption and emissions by 7.66% and 6.77%. It is proved that the proposed method improves the revenue of the whole system, achieves fair revenue distribution, and also improves the energy and environmental benefits of the oil supply chain.

1. Introduction

Promoting the sustainable development of the energy industry is the consensus of all countries. However, fossil fuels like oil still play an important role in this field. The Energy Information Administration (EIA) claims in its latest Short-Term Energy Outlook that global liquid fuel consumption is expected to exceed 100 million barrels per day (b/d) (EIA, 2023). Global oil demand will return to a growth trajectory, driven primarily by growth in China and other non-OECD countries. Improving the energy and environmental performance of the oil supply chain is recognized as a vital way to achieve sustainable development.

This paper focuses on the oil distribution in the downstream oil supply chain, that is, the process of oil products moving from resource centers to demand centers. Oil resource centers are widely distributed depending on oil fields, while oil demand centers are concentrated in economically developed areas. The unbalanced distribution of supply and demand leads to the problems of long transportation distances, complex transportation routes, and high transportation cost (Wei et al., 2022). To solve this problem, individual enterprises have made efforts in the optimization of transportation in the downstream oil supply chain. Transportation structures and cost have been improved to some extent (Pudasaini, 2021). However, individual enterprises focus only on their own expenses and resources. This leads to the underestimation of other nodal enterprises in the same supply chain, resulting in the inefficiency of the entire system.

At present, more and more managers and scholars emphasize the necessity of cooperation among enterprises (Asghari et al., 2022). In the oil industry, oil substitution is a way for oil

* Corresponding author.
** Corresponding author.
E-mail addresses: qliao@cup.edu.cn (Q. Liao), liangyt21st@163.com (Y.-T. Liang).

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enterprises to achieve win-win cooperation. The two oil enterprises buy and sell each other's oil products in each other's hinterlands. This can shorten transportation distances or avoid market shortages, thereby improving the economic and social benefits of the oil supply chain. In addition, pipeline transportation is an effective way to save energy. Reasonable pipeline freight can bring about an increase in pipeline turnover, thus achieving win-win cooperation between the oil shipper and the pipeline operator. The difficulty of cooperation lies in the establishment of coordination methods, including the integration of material flows, capital flows and information flows, and the fair distribution of revenue. However, due to the lack of customized coordination methods, cooperation among different enterprises in the downstream oil supply chain cannot be carried out smoothly in practice.

The motivation of this paper is to propose a multi-party coordination method to promote cooperation between oil shippers and pipeline operator by optimizing oil transportation, oil substitution and pipeline pricing schemes, and ultimately improve the economic, energy and environmental benefits of the entire system. Four questions will be addressed in this paper.

(1) What is the content of cooperation among oil shippers and pipeline operator, and what is the direction of material flows, capital flows and information flows?
(2) How to simulate the operational behavior of all stakeholders, including decision variables, objectives and constraints?
(3) How to guarantee fair revenue distribution to maintain harmonious cooperative relations among stakeholders?
(4) How much economic, energy and environmental benefits can multi-party cooperation bring to the downstream oil supply chain?

The contribution of this paper is as follows.

(1) A multi-party coordination framework among oil shippers and pipeline operator is proposed for the first time to promote energy saving and cost reduction in the downstream oil supply chain.
(2) An integrated game-theoretic modeling and analysis method is developed to simulate the operational behaviors of all stakeholders, including oil transportation, oil substitution and pipeline pricing, and to determine a fair revenue distribution scheme.
(3) Logarithmic transformation and price discretization are used to deal with the non-convex and nonlinear characteristics of the model.
(4) Taking South China as an example, three scenarios of business as usual, two-party cooperation and multi-party coordination are designed for comparative analysis in terms of economic, energy and environmental benefits.

In the field of oil supply chain management, some scholars have conducted relevant studies on supply chain optimization and coordination, which can provide reference and inspiration for our research.

1.1. Oil supply chain optimization

The optimization of the downstream oil supply chain is to make reasonable decisions on oil supply, transportation, inventory, sales and other links under the premise of meeting business requirements. The mathematical programming model is one of the most popular tools to solve this problem (Zhou et al., 2019). Decisions are driven primarily by economic goals, like minimum expense and maximum profit, but also influenced by other goals, such as the shortest lead time and highest customer satisfaction. The decision variables include transportation routes, transportation modes, transportation quantity, inventory level, etc. Constraints include oil supply and demand capacity, transportation capacity, batch requirements, loading and unloading capacity, oil depot capacity, etc. (Fernandes et al., 2014).

Relevant studies on the optimization of the downstream oil supply chain were reviewed by Lima et al. (2016). This problem is divided into three categories according to the time scale, namely strategic optimization, tactical optimization and operational optimization, as shown in Table 1. Strategic optimization refers to the construction or transformation of system structure, including the design of transportation network (Kazemi and Szmerekovsky, 2015), and supply and demand network (Fernandes et al., 2013), generally spanning more than ten years. Wang et al. (2019a) studied the optimization of oil pipeline expansion, established a mixed integer linear programming (MILP) model to determine the optimal pipeline expansion scheme and the corresponding oil transportation scheme. Zhu et al. (2022) analyzed the impact of declining demand for oil products and proposed a MILP model to optimize oil transportation and inventory schemes. Finally, four disposal strategies for improving the utilization rate of oil depots were put forward. Tactical optimization is the decision-making of production, transportation, storage, and other operational schemes, usually spanning weeks or months. Lima et al. (2018) adopted time series analysis and scenario tree analysis to deal with the uncertainty of oil prices and demand. A multi-stage stochastic programming model was built to maximize the profit of the primary distribution of oil products. Subsequently, Lima et al. (2021) considered investment uncertainties and used opportunity-constrained programming to determine the lowest cost design and operation scheme. Jiao et al. (2022) pointed out that there is a mismatch in the distribution of supply and demand in the downstream oil supply chain. To solve this problem, an integrated optimization model of production and transportation was proposed, which can shorten the transportation distance by adjusting the oil product structure on the supply side. Operational optimization involves the operation state of facilities such as pipeline and vehicle scheduling (Tu et al., 2023; Wang et al., 2019b), which are not within the scope of this paper. However, the above studies are all internal optimization from the perspective of a single enterprise, ignoring the potential of inter-enterprise cooperation. If each entity focuses only on its own interests or uses only its own resources, contradictions and conflicts will arise, leading to inefficiency throughout the supply chain.

1.2. Oil supply chain coordination

At present, more and more attention has been paid to the study of supply chain coordination (Mosanna et al., 2022). Compared with supply chain optimization, supply chain coordination is the joint management of the whole or part of the supply chain (Guajardo et al., 2013). The coordination of the supply chain is to realize the cooperation among entities through information sharing, partial and overall optimization, revenue distribution, etc. Arshinder et al. (2008) divided supply chain coordination into coordination among inventory, transportation, forecasting and production, and coordination among purchasers, producers, stockists and distributors.

For the downstream oil supply chain, independent enterprises are managed by different entities. For instance, carriers provide oil transportation services and shippers entrust oil transportation services. Different departments within the same enterprise can also be managed by different entities. For instance, the production department is responsible for oil procurement and processing, the

Table 1
Relative research on optimization of downstream oil supply chain.

Author	Time scale		Model	Objective		Cooperation	Revenue distribution	Real case
	Strategic	Tactical		Min cost	Max profit			
Guajardo et al. (2013)	✓	✓	MINLP		✓		✓	
Fernandes et al. (2013)	✓	✓	MILP		✓			Portugal
Fernandes et al. (2014)	✓	✓	MILP		✓	✓		Portugal
Kazemi and Szmerekovsky (2015)	✓	✓	MILP	✓				America
Lima et al. (2018)		✓	MILP		✓			Portugal
Wang et al. (2019a)	✓	✓	MILP	✓				China
Yuan et al. (2019)		✓	MILP	✓		✓		China
Lima et al. (2021)	✓	✓	MILP	✓				Brazil
Zhu et al. (2022)	✓	✓	MILP	✓				China
Jiao et al. (2022)	✓	✓	MILP	✓				China
Qiu et al. (2022)		✓	MILP	✓				China
This study	✓	✓	MINLP		✓	✓	✓	China

transportation department is responsible for oil delivery and storage, and the sales department is responsible for oil retail. MirHassani (2008) pointed out that the demand for oil products can be effectively satisfied through the coordination of the whole system. In addition, some scholars also paid attention to the coordination between the biofuel supply chain and the oil supply chain to improve the competitiveness of biofuels in terms of cost (Tong et al., 2014). Yuan et al. (2019) set up a MILP model to calculate the economic potential of oil substitution, aiming to minimize logistics cost for both enterprises. However, this model does not consider reasonable revenue distribution between enterprises. In our previous study (Qiu et al., 2023a), we examined cooperation between the oil shipper and the pipeline operator and developed coordination mechanisms based on fair revenue distribution. However, cooperation between oil shippers is neglected. The structure of the downstream oil supply chain is complex and the nodes are widely distributed. Corresponding coordination research is still in the stage of qualitative analysis. It is necessary to conduct quantitative research among different entities and different departments of the same entity to guide the actual operation of oil enterprises.

1.3. Other supply chain coordination

For supply chain coordination, researchers usually design effective mechanisms to regulate the behavior of entities and take incentives to encourage them to participate in cooperation actively. Supply chain contracts is a common form of coordination mechanism, including wholesale price contract, repurchase contract, revenue sharing contract, quantity discount contract, etc. (Guo et al., 2017). The wholesale price contract is popular because of its simple form and convenient execution. The supplier decides the wholesale price and the seller decides the quantity to buy. Cui et al. (2007) proved that under linear demand function and seller's fairness preference, a wholesale price higher than marginal cost can achieve a certain degree of supply chain coordination. Caliskan-Demirag et al. (2010) extended this study by proving that under the nonlinear demand function, if the seller attaches enough importance to fairness, the wholesale price contract can also coordinate the supply chain. For repurchase contracts, at the beginning of the sale, the supplier provides the product to the seller at the wholesale price, and at the end of the sale, the supplier repurchases the reserved products from the seller at the buyback price (Zhao et al., 2014). The supplier helps the seller share the risk of product retention, thereby increasing the seller's enthusiasm to buy the product (Doganoglu and Inceoglu, 2020). For revenue sharing contracts, at the beginning of the sale, the supplier provides the product to the seller at a lower wholesale price, and at the end of the sale, the seller returns the sales revenue to the supplier at a percentage of the sales proceeds (Bart et al., 2019). Pfeiffer (2016) compared revenue sharing contracts with wholesale price contracts and concluded that the former is superior to the latter in cases of greater cost uncertainty. The above research can be used as a reference for this study.

At present, the research of supply chain coordination has gradually developed from two-level supply chains to supply chains with complex structures. The influencing factors also become more complex, such as considering supply and demand uncertainty, fairness and altruism preference, and information symmetry and asymmetry. However, most of the existing studies have simplified the supply chain structure. Accurate modeling of a real supply chain needs to consider the operational constraints of multiple links, which makes it difficult to draw conclusions directly from the formula (Zheng et al., 2020). For the downstream oil supply chain, it is necessary to combine optimization methods and game methods to model and analyze in real business environments. Also, an efficient coordination mechanism should be designed to assist enterprises in decision-making and achieving win-win cooperation.

The rest of this paper is organized as follows. Section 2 answers the content of cooperation among oil shippers and oil carriers. Section 3 presents a mathematical model based on a cooperative game to characterize stakeholders' behaviors. In Section 4, a real case in China is used to calculate the economic, energy and environmental benefits brought by the proposed method. Finally, the conclusion is drawn in Section 5.

2. Problem statement

In the primary distribution of oil products, oil products are delivered from refineries to wholesale or retail depots via pipeline, railway, waterway and roadway (Hong et al., 2023; Lima et al., 2016). In this paper, two types of stakeholders are considered to participate in business cooperation to improve the economic, energy and environmental benefits of the entire system, one is the pipeline operator, and the other is the oil shipper. The schematic diagram is given in Fig. 1.

On the one hand, compared with other transportation modes, pipeline performs better in terms of safety, energy benefits and environmental benefits, like being less affected by weather, lower energy consumption in operation, 24-hour uninterrupted delivery, etc. However, in a competitive transportation market, unreasonable pipeline freight will lead oil shippers with price preferences to reduce pipeline turnover. This will hurt the energy efficiency and environmental benefits of the downstream oil supply chain. Therefore, how to find a balance between pipeline freight and pipeline turnover becomes an urgent task for the pipeline operator

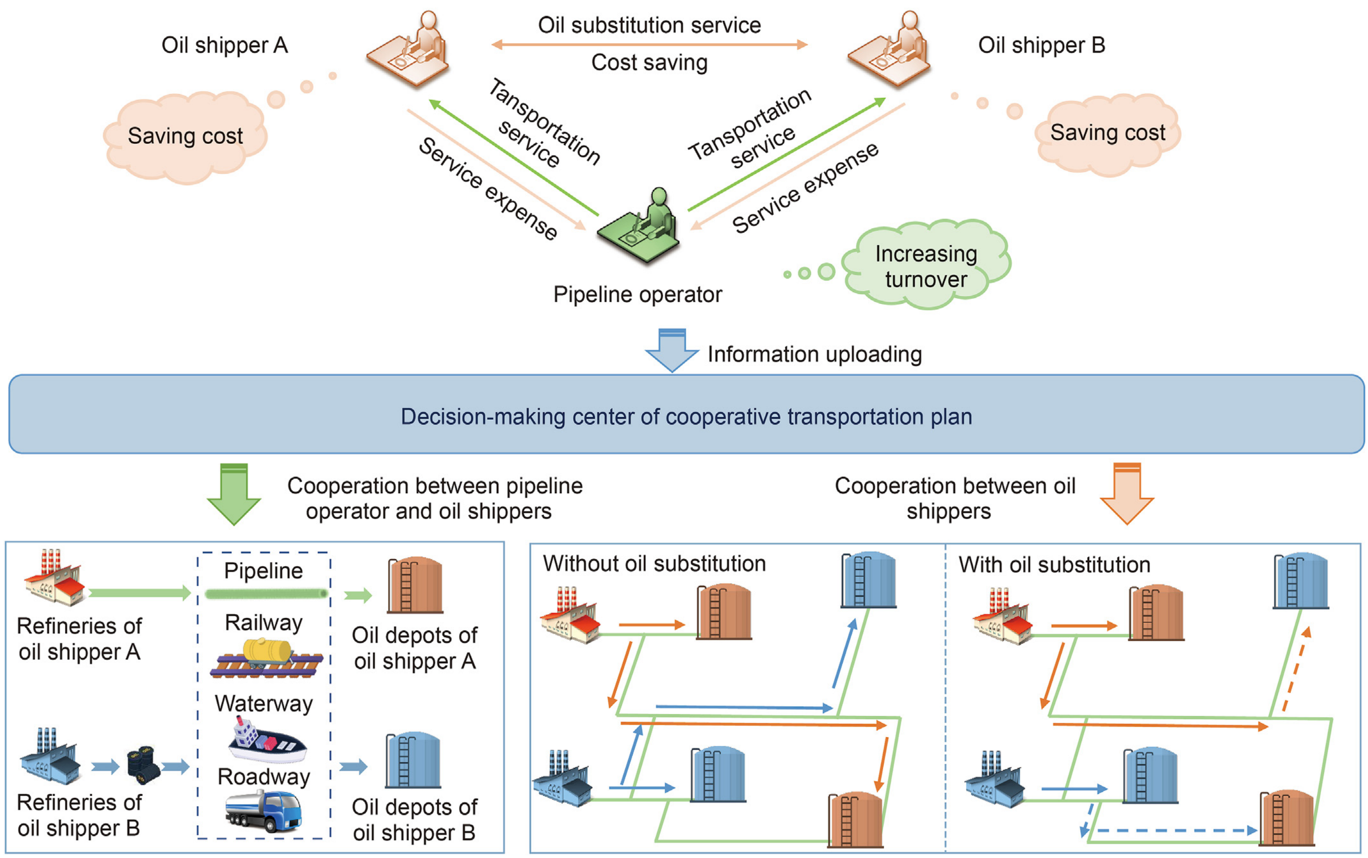

Fig. 1. Cooperation among oil shippers and pipeline operator.

(Liao et al., 2022). On the other hand, oil substitution can alleviate cross-transportation problems and help oil shippers save transportation cost. However, due to the existence of information barriers and the lack of an effective coordination mechanism, this kind of business cannot be carried out smoothly, which harms the economic, energy and environmental benefits of the downstream oil supply chain. Therefore, it is necessary to set up regulations and incentives to consolidate oil shippers' alliance.

The research framework of this paper, as shown in Fig. 2, consists of two modules. In the first module, called business as usual, oil shippers implement transportation planning independently and do not cooperate with other enterprises. After collecting information on oil supply and demand plans, as well as transportation routes, freight and capacity, each oil shipper optimizes individual transportation schemes using the lowest-cost driven model, which is detailed in our previous study (Qiu et al., 2022). In this case, transportation cost for each oil shipper and transportation revenue for the pipeline operator are determined, which is regarded as the baseline.

The second module is the key to this research, that is, multi-party coordination. In this module, an integrated model is developed to simulate the operational behaviors of various stakeholders, including oil transportation and oil substitution optimization for oil shippers, and pricing optimization of the pipeline operator (detailed in Section 3.2). To motivate stakeholders to participate in cooperation, the objective function of the Nash negotiation type is constructed based on cooperative games to improve the revenue of the whole system and achieve a fair revenue distribution (detailed in Section 3.1). Note that the calculation results of the first module, namely the cost of the oil shipper and the revenue of the pipeline operator, are the bottom line of the negotiation. They are taken as inputs to the integrated model. This model belongs to the non-convex mixed integer nonlinear (MINLP) model. Logarithm transformation and price discretization are introduced for model linear approximation (detailed in Section 3.3). Then, the MINLP model can be simplified to the MILP model, which can be solved by the branch and bound method. Finally, simulation experiments are carried out to verify the effectiveness of the proposed method. Coordination schemes include oil transportation and substitution schemes of oil shippers, pricing schemes of the pipeline operator and revenue distribution schemes of all stakeholders. In addition, the energy and environmental benefits will be analyzed in detail through indicators, like annual energy consumption, annual greenhouse gas and atmospheric pollutants (detailed in Section 3.4).

3. Mathematical model

This section presents the integrated MINLP model, including the objective function, constraints, and model linearization procedures. The expression of model sets, parameters and variables can be found in Appendix A.

The key parameters of the model are as follows.

(1) Geographic information: location of refineries and oil depots owned by different oil shippers.
(2) Supply and demand plans: annual production plans of refineries and annual sales plans of oil depots.
(3) Transportation information: mode, distance, freight, and capacity of each transportation route.
(4) Cooperation requirements: each oil shipper's willingness and ability to substitute oil products.

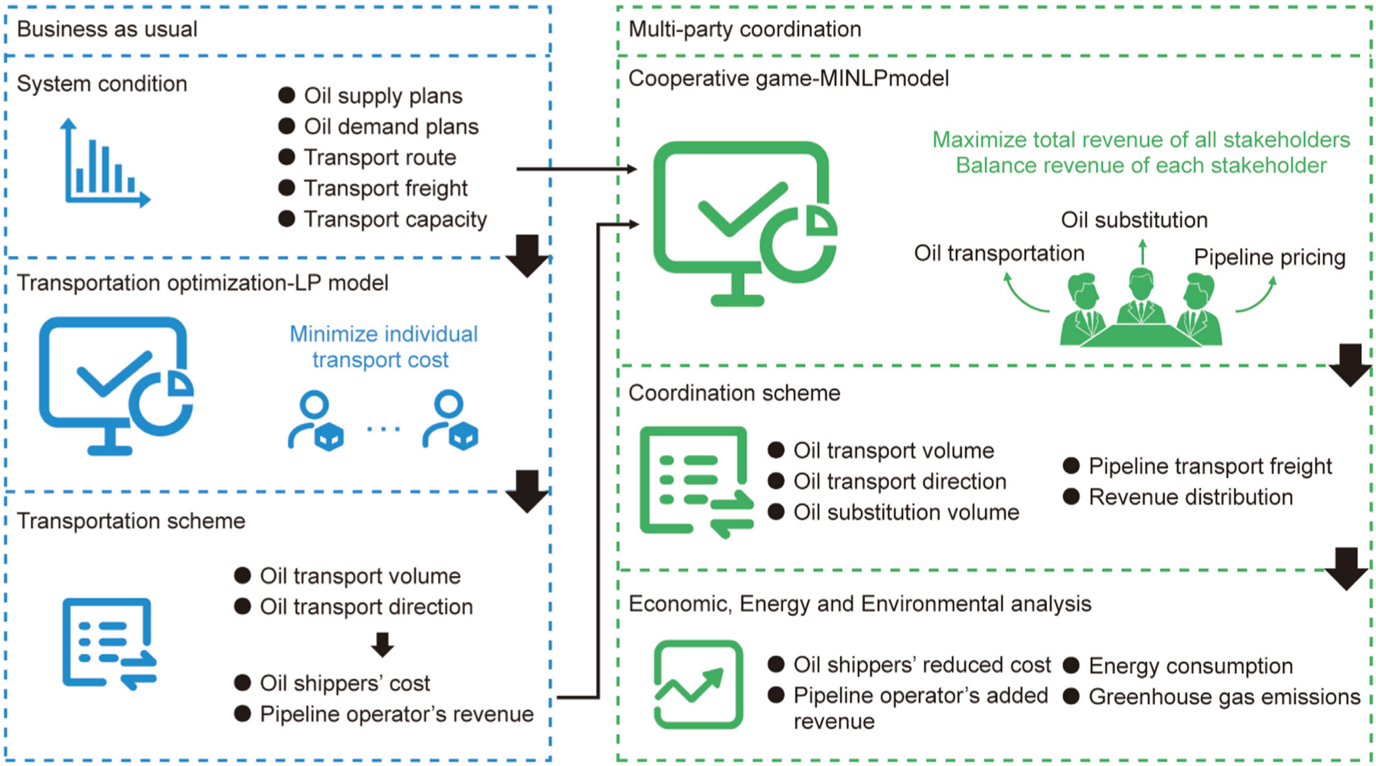

Fig. 2. Research framework of this paper.

(5) Cost information: revenue of pipeline operator and cost of each oil shipper before multi-party cooperation.

The key variables of the model are as follows.

(1) Oil transportation schemes: selection of transportation routes, including transportation mode, quantity and direction.
(2) Oil substitution schemes: quantity and source of substituted oil products for each oil shipper.
(3) Pricing schemes: pipeline freight, oil substitution cost.
(4) Cost results: changes in revenue of pipeline operator and cost of each oil shipper after multi-party cooperation.

The assumptions of the model are as follows.

(1) Transportation information is shared among all stakeholders.
(2) Fluctuations of inventory at the intermediate moment are not considered.
(3) The oil loss caused during transportation is neglected.
(4) Oil can be delivered from refineries to depots on time.

3.1. Objective function

The objective function of the Nash negotiation type in Eq. (1) is adopted to guarantee the maximum revenue of the entire system and the fairness of revenue distribution (Zheng et al., 2020), where $\mathbf{S}$ and $\mathbf{Z}$ are sets of oil shippers and transportation modes, FS_s and FC_z indicate cost decreased by oil shippers and revenue increased by oil carriers after multi-party cooperation, α_s and β_z are the bargaining power of each stakeholder. Here, the pipeline operator is represented by $z = 1$.

$$\max F = \prod_{s \in \mathbf{S}} FS_s^{\alpha_s} \prod_{z=1} FC_z^{\beta_z} \tag{1}$$

Equation (2) calculates cost decreased by oil shippers, where fso_s indicates basic cost before multi-party cooperation. After multi-party cooperation, oil shippers shall not only pay transportation cost (SCV_s) and bear the economic loss caused by supply and demand imbalance (SCS_s) but also pay the oil substitution fee when receiving oil from other oil shippers (SCX_s), as shown in Eqs. (3)–(5). In addition, oil shippers can also earn oil substitution income when supplying oil to other oil shippers (SCY_s), as shown in Eq. (6).

$$FS_s = fso_s - SCV_s + SCS_s + SCX_s - SCY_s, \ \forall s \in \mathbf{S} \tag{2}$$

In Eqs. (3)–(6), SCV_s is determined by the ownership of oil depots $b^{\mathrm{D}}_{j,s}$, unit freight $c^{\mathrm{TRA}}_{i,j,k,z}$, transportation turnover ($l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z}$) and freight adjustment factor (R^{TR}_z), SCS_s is the sum of backlog loss of refineries and stockout loss of oil depots, SCX_s and SCY_s are determined by unit substitution cost ($C^{\mathrm{TC}}_{i,k}$) and substitution volume.

$$SCV_s = \sum_{k \in \mathbf{K}} \sum_{i \in \mathbf{I}} \sum_{j \in \mathbf{J}} \sum_{z \in \mathbf{Z}} b^{\mathrm{D}}_{j,s} R^{\mathrm{TR}}_z c^{\mathrm{TRA}}_{i,j,k,z} l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z}, \ \forall s \in \mathbf{S} \tag{3}$$

$$SCS_s = \sum_{k \in \mathbf{K}} \sum_{i \in \mathbf{I}} b^{\mathrm{R}}_{i,s} c^{\mathrm{RS}}_{i,k} S^{\mathrm{RE}}_{i,k} + \sum_{k \in \mathbf{K}} \sum_{j \in \mathbf{J}} b^{\mathrm{D}}_{j,s} c^{\mathrm{DS}}_{j,k} S^{\mathrm{DE}}_{j,k}, \ \forall s \in \mathbf{S} \tag{4}$$

$$SCX_s = \sum_{k \in \mathbf{K}} \sum_{i \in \mathbf{I}} \sum_{j \in \mathbf{J}} \sum_{z \in \mathbf{Z}} \left(1 - b^{\mathrm{R}}_{i,s}\right) b^{\mathrm{D}}_{j,s} C^{\mathrm{TC}}_{i,k} V^{\mathrm{TRA}}_{i,j,k,z}, \ \forall s \in \mathbf{S} \tag{5}$$

$$SCY_s = \sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{I}}\sum_{j\in\mathbf{J}}\sum_{z\in\mathbf{Z}}\left(1-b^{\mathrm{D}}_{j,s}\right)b^{\mathrm{R}}_{i,s}C^{\mathrm{TC}}_{i,k}V^{\mathrm{TRA}}_{i,j,k,z},\ \forall s\in\mathbf{S} \tag{6}$$

The calculation of revenue increased by oil carriers after multi-party cooperation is given in Eq. (7), where fco_z indicates basic revenue before multi-party cooperation.

$$FC_z = \sum_{k\in\mathbf{K}}\sum_{i\in\mathbf{I}}\sum_{j\in\mathbf{J}}R^{\mathrm{TR}}_z c^{\mathrm{TRA}}_{i,j,k,z} l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z} - fco_z,\ \forall z\in\mathbf{Z} \tag{7}$$

3.2. Constraints

Equations (8) and (9) are mass balance constraints of refineries and oil depots, where oil backlog ($S^{\mathrm{RE}}_{i,k}$) is equal to the planned oil supply ($Q^{\mathrm{RE}}_{i,k}$) minus oil delivered to oil depots, oil stockout ($S^{\mathrm{DE}}_{j,k}$) is equal to planned oil demand ($Q^{\mathrm{DE}}_{j,k}$) minus oil received from refineries. Eq. (10) represents the supply capacity of refineries ($q^{\mathrm{RE,min}}_{i,k}$ and $q^{\mathrm{RE,max}}_{i,k}$) and Eq. (11) represents the demand capacity of oil depots ($q^{\mathrm{DE,min}}_{j,k}$ and $q^{\mathrm{DE,max}}_{j,k}$).

$$\sum_{j\in\mathbf{J}}\sum_{z\in\mathbf{Z}}V^{\mathrm{TRA}}_{i,j,k,z} + S^{\mathrm{RE}}_{i,k} = Q^{\mathrm{RE}}_{i,k},\ \forall k\in\mathbf{K}, i\in\mathbf{I} \tag{8}$$

$$\sum_{i\in\mathbf{I}}\sum_{z\in\mathbf{Z}}V^{\mathrm{TRA}}_{i,j,k,z} + S^{\mathrm{DE}}_{j,k} = Q^{\mathrm{DE}}_{j,k},\ \forall k\in\mathbf{K}, j\in\mathbf{J} \tag{9}$$

$$q^{\mathrm{RE,min}}_{i,k} \le Q^{\mathrm{RE}}_{i,k} \le q^{\mathrm{RE,max}}_{i,k},\ \forall k\in\mathbf{K}, i\in\mathbf{I} \tag{10}$$

$$q^{\mathrm{DE,min}}_{j,k} \le Q^{\mathrm{DE}}_{j,k} \le q^{\mathrm{DE,max}}_{j,k},\ \forall k\in\mathbf{K}, j\in\mathbf{J} \tag{11}$$

The oil substitution rules are expressed in Eqs. (12)–(15). If refinery i is allowed to supply oil product k to oil depots belonging to different shippers ($b^{\mathrm{RC}}_{i,k}=1$), the oil substitution volume shall meet the upper limit ($Q^{\mathrm{RC}}_{i,k} \le q^{\mathrm{RC,max}}_{i,k}$); otherwise, the oil substitution volume is equal to 0. If oil depot j is allowed to receive oil product k from refineries belonging to different shippers ($b^{\mathrm{DC}}_{j,k}=1$), the oil substitution volume shall meet the upper limit ($Q^{\mathrm{DC}}_{j,k} \le q^{\mathrm{DC,max}}_{j,k}$); otherwise, the oil substitution volume is equal to 0.

$$Q^{\mathrm{RC}}_{i,k} \le b^{\mathrm{RC}}_{i,k} q^{\mathrm{RC,max}}_{i,k},\ \forall k\in\mathbf{K}, i\in\mathbf{I} \tag{12}$$

$$Q^{\mathrm{DC}}_{j,k} \le b^{\mathrm{DC}}_{j,k} q^{\mathrm{DC,max}}_{j,k},\ \forall k\in\mathbf{K}, j\in\mathbf{J} \tag{13}$$

$$Q^{\mathrm{RC}}_{i,k} = \sum_{s\in\mathbf{S}}\sum_{j\in\mathbf{J}}\sum_{z\in\mathbf{Z}} b^{\mathrm{R}}_{i,s}\left(1-b^{\mathrm{D}}_{j,s}\right)V^{\mathrm{TRA}}_{i,j,k,z},\ \forall k\in\mathbf{K}, i\in\mathbf{I} \tag{14}$$

$$Q^{\mathrm{DC}}_{j,k} = \sum_{s\in\mathbf{S}}\sum_{i\in\mathbf{I}}\sum_{z\in\mathbf{Z}} b^{\mathrm{D}}_{j,s}\left(1-b^{\mathrm{R}}_{i,s}\right)V^{\mathrm{TRA}}_{i,j,k,z},\ \forall k\in\mathbf{K}, j\in\mathbf{J} \tag{15}$$

Equations (16) and (17) are the transportation capacity constraints of a single route, where $\mathbf{O}$ is the set of oil types. If the route is available to transport oil product k or oil products of type o from refinery i to depot j by mode z ($b^{\mathrm{TRA}}_{i,j,k,z}=1$ or $b^{\mathrm{TRO}}_{i,j,o,z}=1$), the transportation volume needs to meet the upper and lower limits, $v^{\mathrm{TRA,min}}_{i,j,k,z} \le V^{\mathrm{TRA}}_{i,j,k,z} \le v^{\mathrm{TRA,max}}_{i,j,k,z}$; otherwise, the transportation volume is equal to 0.

$$b^{\mathrm{TRA}}_{i,j,k,z} v^{\mathrm{TRA,min}}_{i,j,k,z} \le V^{\mathrm{TRA}}_{i,j,k,z} \le b^{\mathrm{TRA}}_{i,j,k,z} v^{\mathrm{TRA,max}}_{i,j,k,z},\ \forall k\in\mathbf{K}, i\in\mathbf{I}, j\in\mathbf{J}, z\in\mathbf{Z} \tag{16}$$

$$b^{\mathrm{TRO}}_{i,j,o,z} v^{\mathrm{TRO,min}}_{i,j,o,z} \le \sum_{k\in\mathbf{K}} b^{\mathrm{O}}_{k,o} V^{\mathrm{TRA}}_{i,j,k,z} \le b^{\mathrm{TRO}}_{i,j,o,z} v^{\mathrm{TRO,max}}_{i,j,o,z},\ \forall o\in\mathbf{O}, i\in\mathbf{I}, j\in\mathbf{J}, z\in\mathbf{Z} \tag{17}$$

3.3. Model reformulation

The objective function in Eq. (1) is highly non-convex and nonlinear. In the following, logarithm transformation and piecewise linearization are introduced for model linear approximation (Qiu et al., 2023b). Firstly, logarithmic transformation is adopted to transform the objective function from product form into sum form, as shown in Eq. (18).

$$\max \ln F = \sum_{s\in\mathbf{S}}\alpha_s \ln FS_s + \sum_{z=1}\beta_z \ln FC_z \tag{18}$$

Eq. (18) is still a nonlinear equation. Variables YS_s and YC_z are introduced for piecewise linearization of $\ln FS_s$ and $\ln FC_z$. The linear expressions of YS_s and YC_z are presented in Eqs. (19)–(21), where ε_e and θ_e are linearized parameters in revenue-added interval e.

$$\max \ln F = \sum_{s\in\mathbf{S}}\alpha_s YS_s + \sum_{z=1}\beta_z YC_z,\ YS_s = \ln FS_s,\ YC_z = \ln FC_z \tag{19}$$

$$\varepsilon_e FS_s + \theta_e + (BS_{s,e}-1)M \le YS_s \le \varepsilon_e FS_s + \theta_e + (1-BS_{s,e})M,\ \forall e\in\mathbf{E}, s\in\mathbf{S} \tag{20}$$

$$\varepsilon_e FC_z + \theta_e + (BC_{z,e}-1)M \le YC_z \le \varepsilon_e FC_z + \theta_e + (1-BC_{z,e})M,\ \forall e\in\mathbf{E}, z=1 \tag{21}$$

As shown in Eqs. (22) and (23), $BS_{s,e}$ and $BC_{z,e}$ are variables that determine the range of added revenue of oil shippers and oil carriers. For example, if the added revenue of oil shippers is in interval e, that is $y^{\min}_e \le FS_s \le y^{\max}_e$, $BS_{s,e}=1$; otherwise, $BS_{s,e}=0$.

$$y^{\min}_e + (BS_{s,e}-1)M \le FS_s \le y^{\max}_e + (1-BS_{s,e})M,\ \forall e\in\mathbf{E}, s\in\mathbf{S} \tag{22}$$

$$y^{\min}_e + (BC_{z,e}-1)M \le YC_z \le y^{\max}_e + (1-BC_{z,e})M,\ \forall e\in\mathbf{E}, z=1 \tag{23}$$

Each stakeholder's added revenue can only exist within one range, as seen in Eqs. (24) and (25).

$$\sum_{e\in\mathbf{E}} BS_{s,e} = 1,\ \forall s\in\mathbf{S} \tag{24}$$

$$\sum_{e\in\mathbf{E}} BC_{z,e} = 1,\ \forall z=1 \tag{25}$$

There are nonlinear terms $R^{\mathrm{TR}}_z V^{\mathrm{TRA}}_{i,j,k,z}$ and $C^{\mathrm{TC}}_{i,k}V^{\mathrm{TRA}}_{i,j,k,z}$ in Eqs. (3)–(7). In the following, price discretization is adopted for model linearization. $R^{\mathrm{TR}}_z V^{\mathrm{TRA}}_{i,j,k,z}$ is replaced by $PX^{\mathrm{TRB}}_{i,j,k,z}$ in Eq. (26) and $C^{\mathrm{TC}}_{i,k}V^{\mathrm{TRA}}_{i,j,k,z}$ is replaced by $PX^{\mathrm{TRC}}_{i,j,k,z}$ in Eq. (27).

$$PX^{\mathrm{TRB}}_{i,j,k,z} = R^{\mathrm{TR}}_{z} V^{\mathrm{TRA}}_{i,j,k,z},\ \forall k \in \mathbf{K}, i \in \mathbf{I}, j \in \mathbf{J}, z \in \mathbf{Z} \tag{26}$$

$$PX^{\mathrm{TRC}}_{i,j,k,z} = C^{\mathrm{TC}}_{i,k} V^{\mathrm{TRA}}_{i,j,k,z},\ \forall k \in \mathbf{K}, i \in \mathbf{I}, j \in \mathbf{J}, z \in \mathbf{Z} \tag{27}$$

Equation (28) is the expression of $PX^{\mathrm{TRB}}_{i,j,k,z}$. If transportation freight a is selected by oil carrier z ($BPT_{z,a}=1$), $PX^{\mathrm{TRB}}_{i,j,k,z} = r^{\mathrm{PT}}_{z,a} V^{\mathrm{TRA}}_{i,j,k,z}$. Eq. (29) is the expression of $PX^{\mathrm{TRC}}_{i,j,k,z}$. If oil substitution cost c of oil product k is selected by refinery i ($BPC_{i,k,c}=1$), $PX^{\mathrm{TRC}}_{i,j,k,z} = c^{\mathrm{PC}}_{i,k,c} V^{\mathrm{TRA}}_{i,j,k,z}$.

$$r^{PT}_{z,a} V^{\mathrm{TRA}}_{i,j,k,z} + (BPT_{z,a} - 1)M \le PX^{\mathrm{TRB}}_{i,j,k,z} \le r^{PT}_{z,a} V^{\mathrm{TRA}}_{i,j,k,z} + (1 - BPT_{z,a})M,\ \forall a \in \mathbf{A}, k \in \mathbf{K}, i \in \mathbf{I}, j \in \mathbf{J}, z \in \mathbf{Z} \tag{28}$$

$$c^{PC}_{i,k,c} V^{\mathrm{TRA}}_{i,j,k,z} + (BPC_{i,k,c} - 1)M \le PX^{\mathrm{TRC}}_{i,j,k,z} \le c^{PC}_{i,k,c} V^{\mathrm{TRA}}_{i,j,k,z} + (1 - BPC_{i,k,c})M,\ \forall c \in \mathbf{C}, k \in \mathbf{K}, i \in \mathbf{I}, j \in \mathbf{J}, z \in \mathbf{Z} \tag{29}$$

Only one transportation freight can be selected by each oil carrier and only oil substitution cost can be selected by each refinery, as shown in Eqs. (30) and (31).

$$\sum_{a \in \mathbf{A}} BPT_{z,a} = 1,\ \forall z \in \mathbf{Z} \tag{30}$$

$$\sum_{c \in \mathbf{C}} BPC_{i,k,c} = 1,\ \forall k \in \mathbf{K}, i \in \mathbf{I} \tag{31}$$

3.4. Energy and environmental evaluation

In this study, four indicators are used for energy and environmental benefit evaluation in the downstream oil supply chain, called annual energy consumption TEE, annual greenhouse gas and atmospheric pollutants emissions TGG_g, specific energy consumption UEE, specific greenhouse gas and atmospheric pollutants emissions UGG_g (Yuan et al., 2019). The expressions are shown in Eqs. (32)–(36). Here, ue_z is the unit turnover energy consumption for mode z, $ug_{z,g}$ is the unit turnover emission of greenhouse gas and atmospheric pollutant g for mode z, TVV is the annual transportation turnover of oil products.

$$TEE = \sum_{i \in \mathbf{I}} \sum_{j \in \mathbf{J}} \sum_{k \in \mathbf{K}} \sum_{z \in \mathbf{Z}} ue_z l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z} \tag{32}$$

$$TGG_g = \sum_{i \in \mathbf{I}} \sum_{j \in \mathbf{J}} \sum_{k \in \mathbf{K}} \sum_{z \in \mathbf{Z}} ug_{z,g} l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z} \tag{33}$$

$$TVV = \sum_{i \in \mathbf{I}} \sum_{j \in \mathbf{J}} \sum_{k \in \mathbf{K}} \sum_{z \in \mathbf{Z}} l^{\mathrm{TRA}}_{i,j,z} V^{\mathrm{TRA}}_{i,j,k,z} \tag{34}$$

$$UEE = \frac{TEE}{TVV} \tag{35}$$

$$UGG_g = \frac{TGG_g}{TVV} \tag{36}$$

4. Case study

4.1. Basic data

The proposed method is applied to the primary distribution system of oil products of two state-owned enterprises in South China. At present, the two enterprises optimize individual transportation schemes separately and entrust oil carriers to deliver oil products from refineries to oil depots. PipeChina, the pipeline operator, provides basic pipeline transportation services for both enterprises. To realize cost reduction for oil shippers and revenue increase for the pipeline operator, it is assumed that three enterprises enter into the cooperation mentioned in Section 2 through the intermediary of PipeChina.

One-year oil distribution plans for two oil enterprises are collected, including oil supply plans, oil demand plans, transportation routes and cost information. Fig. 3 shows the annual supply plans of refineries, where shipper 1's refinery is numbered R1–R9 and shipper 2's refinery is numbered R10–R28. Fig. 4 shows the annual demand plans of oil depots, where shipper 1's oil depots are numbered D1–D55 and shipper 2's oil depots are numbered D56–D79. If oil substitution services are available, oil products can

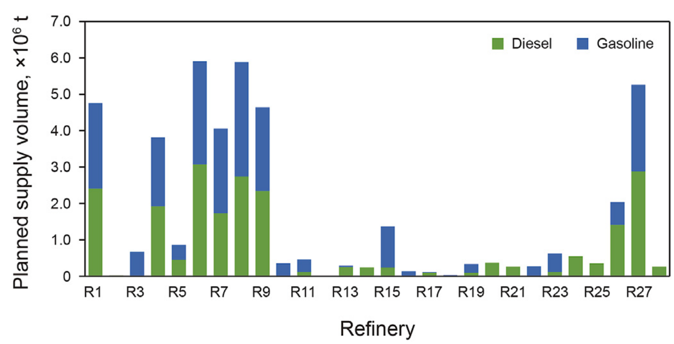

Fig. 3. Supply plans of refineries.

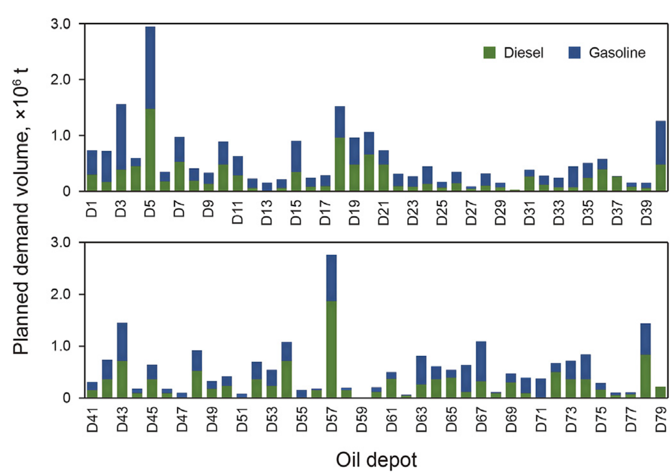

Fig. 4. Demand plans of oil depots.

Table 2
Transportation information.

Start	End	Mode	Freight	Start	End	Mode	Freight	Start	End	Mode	Freight, CNY/t
R1	D56	Pipe	244	R5	D77	Water	448	R9	D63	Pipe	233
	D57	Pipe	244		D79	Water	407		D64	Water	71
	D62	Pipe	275	R6	D63	Pipe	13		D67	Pipe	87
	D69	Pipe	187		D71	Pipe	8		D69	Pipe	269
	D75	Pipe	222	R7	D56	Pipe	418		D71	Pipe	305
	D77	Pipe	259		D57	Pipe	418		D74	Pipe	264
R3	D71	Water	194		D62	Pipe	449	R15	D31	Water	212
R4	D56	Pipe	282		D63	Pipe	116		D43	Water	218
	D57	Pipe	282		D69	Pipe	361	R16	D31	Water	262
	D62	Pipe	313		D71	Water	99	R19	D21	Water	201
	D64	Pipe	213		D74	Pipe	115	R20	D31	Water	234
	D64	Rail	266		D75	Pipe	396		D3	Water	238
	D67	Pipe	213		D76	Rail	302	R22	D3	Water	248
	D67	Rail	266		D77	Pipe	433	R23	D21	Rail	348
	D69	Pipe	225		D77	Rail	280	R24	D31	Rail	172
	D75	Pipe	260	R8	D74	Pipe	191		D21	Rail	155
	D76	Rail	276		D75	Rail	255	R25	D43	Rail	305
	D77	Pipe	297		D77	Pipe	191		D43	Rail	296
	D79	Pipe	256		D64	Rail	255	R26	D48	Pipe	1
R5	D56	Water	433		D64	Rail	268		D43	Pipe	1
	D57	Water	433		D67	Pipe	296		D48	Pipe	36
	D62	Water	464		D67	Pipe	234		D52	Pipe	15
	D63	Water	150	R9	D77	Pipe	290	R27	D19	Rail	142
	D64	Water	364		D79	Pipe	290		D53	Rail	39
	D67	Water	364		D71	Pipe	321		D54	Rail	22
	D69	Water	376		D56	Pipe	88		D43	Pipe	5
	D74	Water	149		D57	Pipe	222		D49	Rail	9
	D75	Water	411		D62	Pipe	222				

be delivered between refineries and oil depots affiliated with different oil shippers. Table 2 presents corresponding route information, including starting point, ending point, transportation mode and freight.

4.2. Economy, energy and environment analysis

Three scenarios are set up for comparative analysis, namely business as usual, two-party cooperation and multi-party coordination. In the scenario of business as usual, the oil substitution service is not available and the pipeline freight is fixed (Wang et al., 2019a). In the scenario of two-party cooperation, the oil substitution service is available, but the revenue distribution between stakeholders is ignored (Yuan et al., 2019). In the scenario of multi-party coordination proposed in this study, the oil substitution service is available and the pipeline freight is adjustable. Also, revenue distribution among all stakeholders is considered. Three scenarios are programmed in the General Algebraic Modeling System (GAMS) Distribution 29.1.0 and solved by GUROBI solver on a personal computer with Intel Core i7-8565U CPU @1.80 GHz 1.99 GHz. The calculation results are displayed in Table 3.

The economic comparison is shown in Fig. 5. In the first scenario, both oil shippers are driven by the lowest transportation cost, which is 4.052 billion CNY and 2.064 billion CNY respectively. The pipeline operator earns 3.186 billion CNY for providing pipeline transportation services. The second scenario aims to minimize the total transportation cost of both oil shippers, and the transportation routes between refineries and oil depots affiliated with different oil shippers are taken into consideration. Compared with the first scenario, the total transportation cost of both oil shippers is reduced by 188 million CNY. However, unfair revenue distribution makes cooperation impossible in the real world. For oil shipper 1, the cost is reduced by 257 million CNY, but for oil shipper 2, the cost is increased by 69 million CNY. It can be seen from the figure that the revenue of the pipeline operator is also reduced by 84 million CNY. In the third scenario, the two oil shippers and the pipeline operator join in the cooperation, and fair revenue distribution is the precondition for this cooperation. In this scenario, the increased

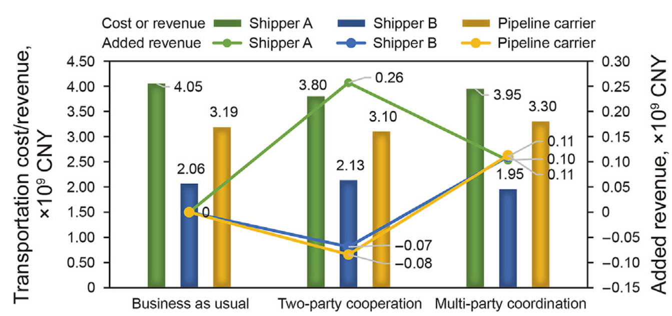

Fig. 5. Economic comparison of three scenarios.

Table 3
Calculation results of three scenarios.

Scenario	Model	Number of variables		Number of constraints	Gap, %	CPU time, s
		Continuous	Discrete			
Business as usual	LP	835	0	1477	0	0.70
Two-party cooperation	LP	988	0	1783	0	0.71
Multi-party coordination	MILP	2393	1526	51852	0	131.45

Table 4
Comparison of transportation volume of three scenarios.

Scenario	Oil shipper	Transportation volume, × 10^6 t				
		Pipeline	Railway	Waterway	Roadway	Sum
Business as usual	Shipper 1	24.12	2.06	3.50	0.93	30.61
	Shipper 2	4.79	4.43	4.10	0.00	13.33
	Sum	28.92	6.49	7.61	0.93	43.94
Two-party cooperation	Shipper 1	23.13	3.51	3.24	0.73	30.61
	Shipper 2	6.76	2.73	3.84	0.00	13.33
	Sum	29.90	6.24	7.08	0.73	43.94
Multi-party coordination	Shipper 1	22.99	2.42	4.14	1.06	30.61
	Shipper 2	7.45	3.13	2.75	0.00	13.33
	Sum	30.44	5.54	6.89	1.06	43.94

revenue of the three stakeholders reaches 326 million CNY. The cost of oil shipper 1 and oil shipper 2 is decreased by 103 million CNY and 110 million CNY respectively. As the pipeline turnover increased from 1.63 to 1.72 billion t·km, the pipeline operator's revenue is also increased by 113 million CNY. The results show that the proposed multi-party coordination method not only improves the total revenue of stakeholders but also makes the revenue distribution more equitable, which can stimulate the active participation of stakeholders in cooperation.

Table 4 and Table 5 compare the transportation volume and cost of pipeline, railway, waterway and roadway in three scenarios. In the second scenario, oil products can be supplied by nearby refineries affiliated with different oil shippers. The volume of pipeline transportation is increased by 0.98 million tons, while that of other modes is decreased by the same amount, including 0.25 million tons for the railway, 0.53 million tons for the waterway and 0.2 million tons for the roadway. The decline in transportation volume also brought a drop in transportation cost, with railway and waterway cost falling by 53 million CNY and 52 million CNY. Despite the increase in pipeline transportation volume, pipeline cost is decreased by 84 million CNY, indicating more use of short-distance pipelines with lower freight rates. The biggest difference in cost variation between the two oil shippers comes from the pipeline, which damages the interests of oil shipper 2 and is not conducive to two-party cooperation. In the third scenario, the pipeline operator can also improve his competitiveness through freight adjustment. The pipeline transportation volume is increased sharply by 1.52 million tons, while that of railway and waterway is decreased by 0.94 million tons and 0.71 million tons. This change is due to the reduction of unit turnover freight of the pipeline from 0.196 to 0.192 CNY, and oil shippers prefer to choose cheaper pipelines for oil transportation. The change in transportation volume brings the change in transportation cost. The transportation cost of the pipeline is increased by 113 million CNY, and that of the railway and waterway is decreased by 259 million CNY and 67 million CNY, respectively. In this scenario, all stakeholders benefit

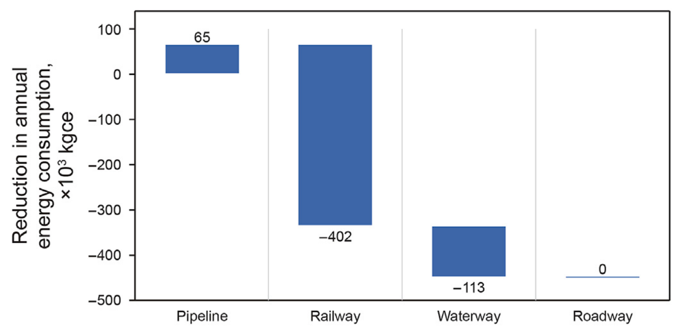

Fig. 6. Reduction in energy consumption in multi-party coordination.

from cooperation. The cost of both oil shippers is decreased, 126 million CNY for shipper 1 and 87 million for shipper 2. In addition, the pipeline operator also gains 113 million CNY by adjusting pipeline freight.

In addition to economic benefits, multi-party coordination can also bring energy and environmental benefits, as shown in Figs. 6 and 7. In this study, the unit turnover energy consumption of

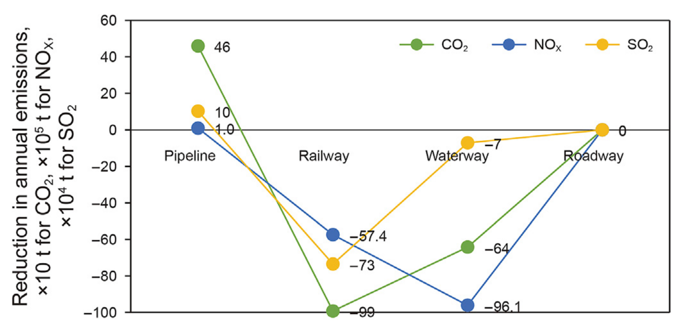

Fig. 7. Reduction in greenhouse gas and atmospheric pollutants in multi-party coordination.

Table 5
Comparison of transportation cost of three scenarios.

Scenario	Oil shipper	Transportation cost, × 10^9 CNY				
		Pipeline	Railway	Waterway	Roadway	Sum
Business as usual	Shipper 1	3.09	0.57	0.40	0.00	4.05
	Shipper 2	0.10	1.03	0.93	0.00	2.06
	Sum	3.19	1.60	1.33	0.00	6.12
Two-party cooperation	Shipper 1	2.53	0.84	0.43	0.00	3.80
	Shipper 2	0.57	0.70	0.85	0.00	2.13
	Sum	3.10	1.55	1.28	0.00	5.93
Multi-party coordination	Shipper 1	2.73	0.56	0.64	0.00	3.93
	Shipper 2	0.57	0.78	0.62	0.00	1.98
	Sum	3.30	1.34	1.27	0.00	5.90

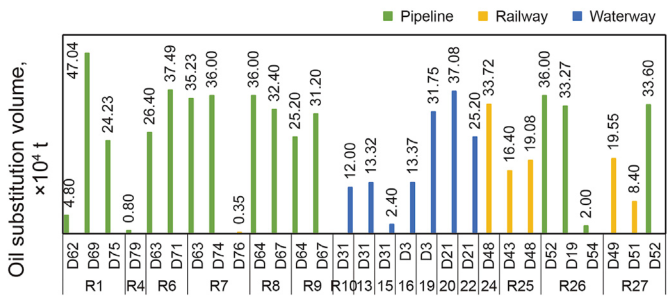

Fig. 8. Oil substitution volume.

pipeline, railway, waterway and roadway is taken as 0.000705, 0.0047, 0.0028 and 0.019 kgce, respectively. As can be seen from Fig. 6, compared with the business as usual scenario, the reduction in annual energy consumption in multi-party coordination reaches 0.45 million kgce. Specifically, the increase in pipeline transportation results in an increase in energy consumption to 0.065 million kgce. While the decrease in railway and waterway transportation results in a decrease in energy consumption to 0.402 and 0.113 million kgce. Overall, the specific energy consumption is reduced from 0.00199 to 0.00186 kgce/(t·km). Emissions of greenhouse gas and atmospheric pollutants include the emissions of carbon dioxide (CO_2), nitrogen oxides (NO_X) and sulfur dioxide (SO_2). The unit turnover emission of the pipeline is the lowest (4.96 g, 1.04 kg and 1.1 kg), followed by railway (11.59 g, 67 kg, 8.58 kg), waterway (15.9 g, 238 kg, 1.75 kg) and roadway (29.98 g, 189.78 kg, 4.56 kg). As shown in Fig. 7, the CO_2, NO_X, and SO_2 emissions in multi-party coordination are reduced by 1.17 million kg, 15.20 million tons, and 0.7 million tons. The specific emission of CO_2, NO_X, and SO_2 is reduced from 9.1 to 8.8 g/(t·km), from 77.1 to 72.8 kg/(t·km), from 2.6 to 2.4 kg/(t·km). It can be concluded that multi-party coordination has positive energy and environmental impacts on the downstream oil supply chain. This is attributed to the reduction in long-distance transportation due to oil substitution and the increase in the proportion of pipeline transportation due to freight adjustment.

4.3. Oil substitution and transportation scheme

This section provides a detailed analysis of oil substitution schemes and oil transportation schemes in the scenario of multi-party coordination. To reduce transportation cost, oil shippers join in cooperation for oil substitution. Figs. 8 and 9 show the volume and price of oil substitution between the two oil shippers. In Fig. 8, six refineries (R1, R4, R6, R7, R8 and R9) affiliated with oil shipper 1 supply 3.37 million tons of oil products via pipeline and railway to thirteen oil depots affiliated with oil shipper 2. In return, eleven refineries (R10, R13, R15, R16, R19, R20, R22, R24, R25, R26 and R27) affiliated with oil shipper 2 supply equivalent volume of oil products via pipeline, railway and waterway to eleven oil depots affiliated with oil shipper 1. In this way, both oil shippers reach a balance between oil supply and demand, and the transportation distance is shortened. The oil substitution price is used to ensure a fair distribution of revenue between oil shippers. If one shipper reduces excessive transportation cost after oil substitution, the other shipper can charge a higher oil substitution fee, so that the two oil shippers can achieve a balance of cost reduction. In Fig. 9, oil shipper 1 has an average substitution price of 10.4 CNY for diesel and 11.2 CNY for gasoline, and oil shipper 2 has an average substitution price of 14.8 CNY for diesel and 11.3 CNY for gasoline. As can be seen from Table 5, the transportation cost of shipper 1 and shipper 2 is decreased by 126 million CNY and 87 million CNY respectively. Shipper 1 has more cost reduction. Thus, in the coordination scheme, shipper 2 charges a higher oil substitution fee.

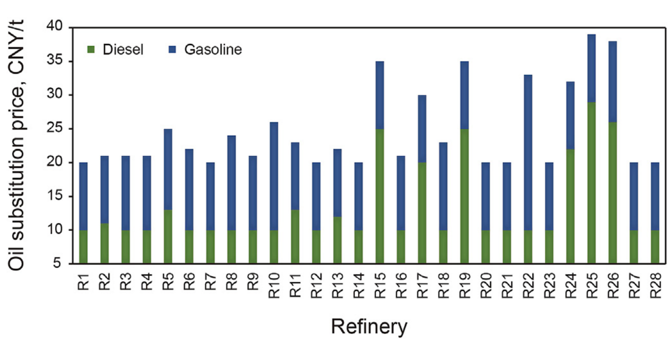

Fig. 9. Oil substitution price.

The schematic diagrams of oil transportation are presented in Figs. 10 and 11. The circle in the figure indicates the location of refineries and the quantity of oil products supplied. The larger the circle, the larger the quantity. The black circle represents oil shipper 1's refineries and the red circle represents oil shipper 2's refineries. Fig. 10 shows the oil transportation scheme to meet the demand of oil shipper 1's oil depots. For oil shipper 1, 84% of oil products are supplied by its own refineries nearby, 5% are transported remotely from its own refineries in the coastal areas, and the remaining 11% are transported from oil shipper 2's refineries. Taking Guangdong and Guangxi provinces as an example, oil products in Guangdong are supplied by local refineries (R6, R8) and refineries in Hainan (R7) through the Pearl River Delta pipeline, by local refinery (R4) via roadway, and by refineries in Shandong and Shanghai (R3, R5) via waterway. In addition, benefiting from the cooperation of oil substitution, oil products are also transported to Guangdong from oil shipper 2's refineries (R19, R20 and R22) via waterway. Oil products in Guangxi are supplied by local refineries (R1) through the Southwest pipeline and roadway, and by refineries in Guangdong and Hainan (R4, R6, R7, R9) through the Southwest pipeline and waterway. Fig. 11 shows the oil transportation scheme to meet the demand of oil shipper 2's oil depots. In South China, oil shipper 2 owns fewer refineries. For oil shipper 2, 46% of the oil products are supplied by its own refineries nearby, 23% are transported remotely from its own refineries in the coastal areas, 6% are transported from its own refineries in the inland areas, the remaining 25% are transported from oil shipper 1's refineries. Taking Guizhou and Yunnan provinces as an example, oil products in Guizhou are supplied by refineries in Sichuan and Ningxia (R23, R24) via railway. In addition, oil products are also transported to Guizhou from oil shipper 1's refineries (R4, R8 and R9) via pipeline. Oil products in Yunnan are supplied by local refineries (R26, R27) via pipeline and railway. Oil products are also transported to Yunnan from oil shipper 1's refinery (R1) via pipeline.

Table 4 shows that in the multi-party coordination scheme, oil products can be supplied by refineries of other shippers nearby, and the pipeline operator can also increase his competitiveness through freight adjustment, resulting in a substantial increase in pipeline transportation and a substantial decrease in railway and waterway transportation. Fig. 12 shows the changes in the volume of four transportation modes of each oil depot in the multi-party coordination scheme. In the figure, solid circles indicate rising transportation volume, while hollow circles indicate falling transportation volume. The bigger the circle, the bigger the change. Taking Guizhou Province as an example, for oil depots D43 and D48, pipeline transportation is decreased by 160,000 and 530,000 tons, while railway transportation is increased by the same amount. For

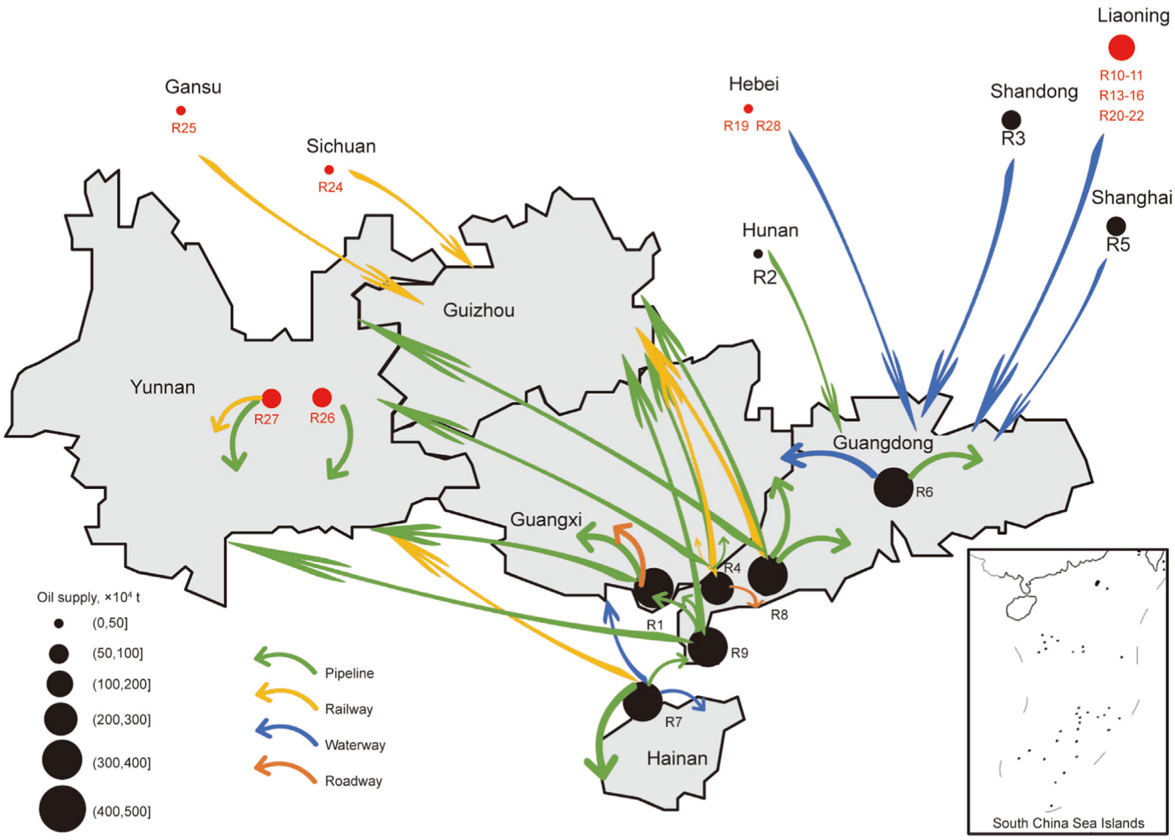

Fig. 10. Oil transportation plan of oil shipper 1.

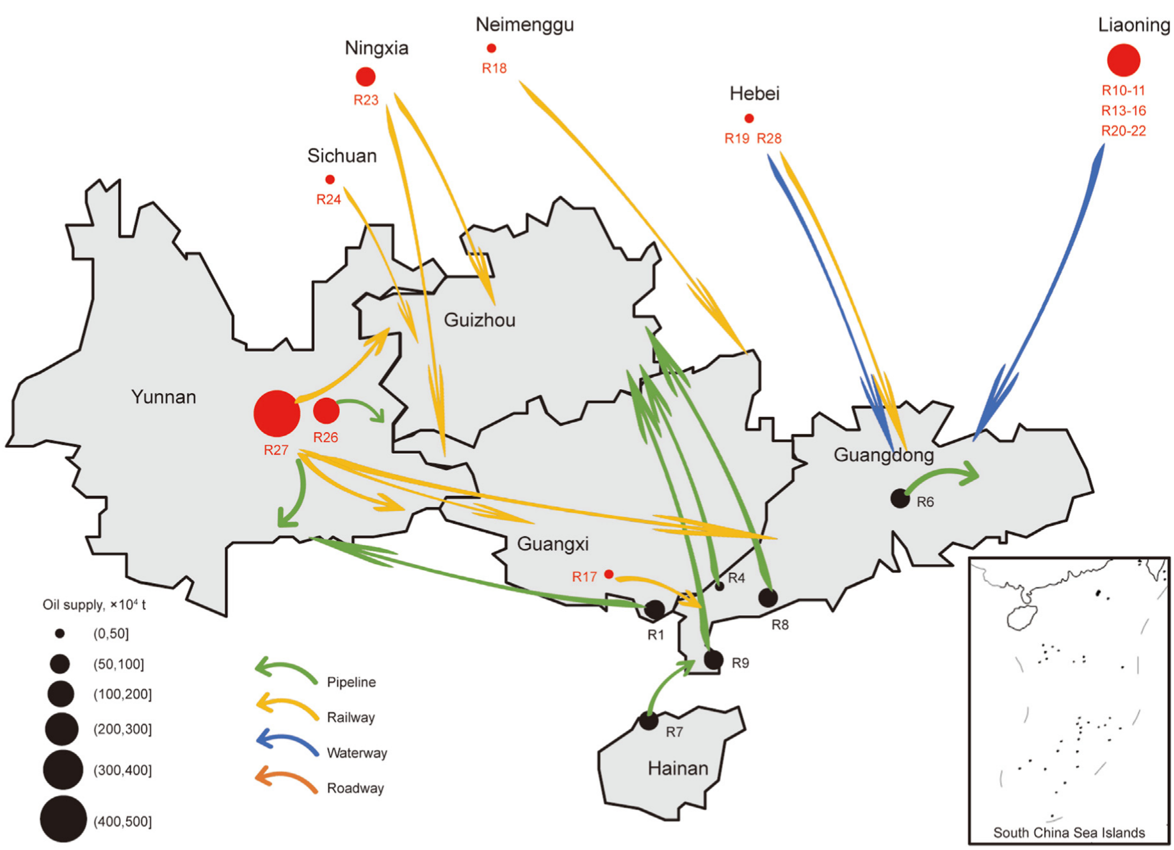

Fig. 11. Oil transportation plan of oil shipper 2.

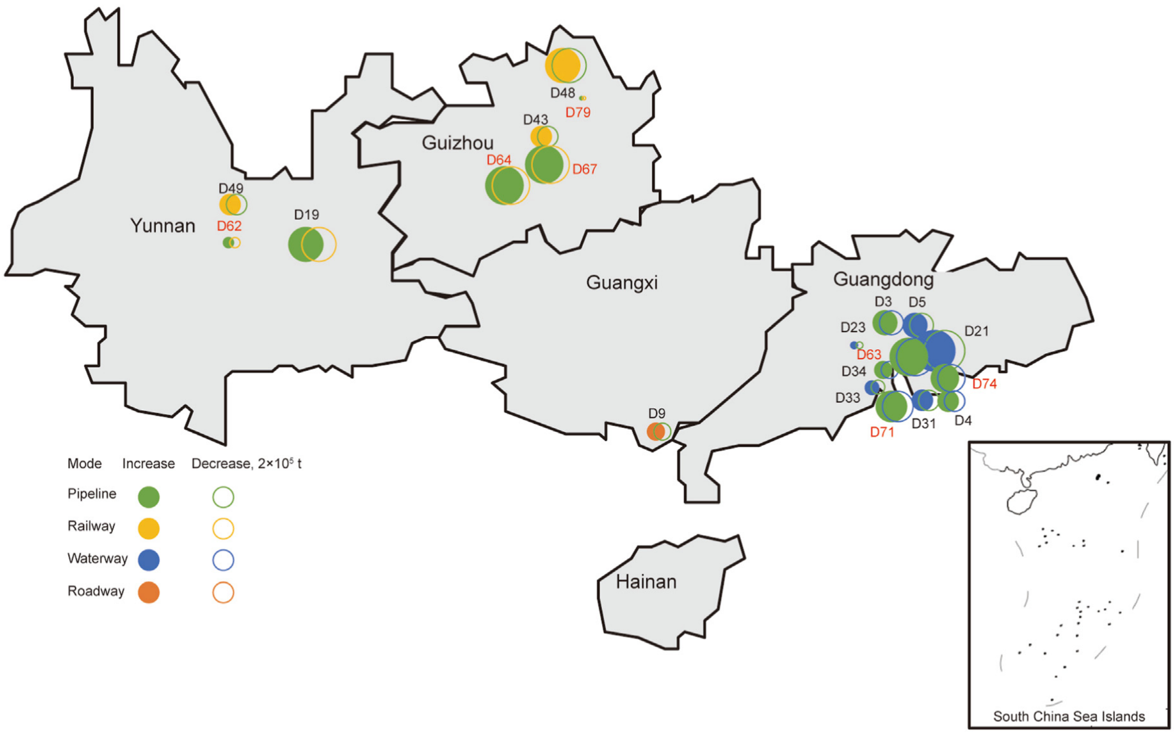

Fig. 12. Changes in oil transportation.

oil depots D64, D67 and D79, pipeline transportation is increased by 610,000, 640,000 and 10,000 tons, while railway transportation is decreased by the same amount. Overall, pipeline transportation in this region is increased by 570,000 tons, while railway transportation is decreased by the same amount, improving the competitiveness of pipelines.

5. Conclusions

To promote win-win cooperation among oil enterprises, this paper proposes a multi-party coordination approach to jointly optimize oil transportation, oil substitution and pipeline pricing schemes. Firstly, the objective function of the Nash negotiation type is constructed to improve the revenue of the entire system and realize the fair distribution of revenue. Next, an integrated MINLP model is developed to simulate the operational behaviors of various stakeholders. Then, logarithm transformation and price discretization methods are introduced for linear approximation of the model. Thus, the MINLP model can be simplified to the MILP model and solved by the branch and bound method. Finally, simulation experiments are carried out in the oil distribution systems of two state-owned enterprises in South China.

The main findings are as follows.

(1) Compared with the business as usual scheme, both two-party cooperation and multi-party coordination schemes can improve the revenue of the entire system. The multi-party coordination has better economic benefits, and the total revenue is further increased by 1.48%.
(2) Compared with two-party cooperation, multi-party coordination can provide a fairer revenue distribution scheme and promote cooperation among oil enterprises. The two oil shippers reduce cost by 2.54% and 5.34% respectively, and the pipeline operator increases revenue by 3.54%.
(3) Multi-party coordination helps to increase pipeline turnover by 5.7%, improving the distribution pattern of oil products.
(4) Multi-party coordination helps to reduce specific energy consumption by 12.64% and specific emissions of greenhouse gas and atmospheric pollutants by 11.79%, bringing positive energy and environmental benefits.

The proposed method can provide scientific guidance for managers to implement cooperation among oil enterprises. Meanwhile, the implementation of the method needs the support of the government. Policy recommendations are as follows.

(1) The construction of oil pipelines should be accelerated and pipeline interconnection should be strengthened, which can provide more economical options for oil transportation.
(2) The oil quality should be supervised strictly and oil measurement should be standardized, which is the guarantee for oil substitution.
(3) Oil substitution among large oil enterprises should be encouraged. It should be piloted on a small scale and then promoted nationwide.
(4) A pipeline capacity trading platform is necessary, which can disclose pipeline capacity information and support oil enterprises to apply for oil substitution services.

In the future, this study can be further expanded in the following aspects. Firstly, the uncertainty of oil demand and production needs to be taken into account in strategic planning. Secondly, pipeline pricing strategies can be further refined to distinguish between fixed cost and usage cost, which helps to reduce the operational risk of pipeline operators. In addition, multimodal transportation should be adopted in the transportation process to further optimize the distribution pattern of oil products.

Declaration of competing interest

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

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Appendix A

Sets and indices

$a\in\mathbf{A}$	Set of discrete coefficients of transportation freight
$c\in\mathbf{C}$	Set of discrete prices for oil substitution
$e\in\mathbf{E}$	Set of stakeholders' revenue-added interval
$i\in\mathbf{I}$	Set of refineries
$j\in\mathbf{J}$	Set of oil depots
$k\in\mathbf{K}$	Set of oil products
$o\in\mathbf{O}$	Set of oil types
$s\in\mathbf{S}$	Set of oil shippers
$z\in\mathbf{Z}$	Set of transportation modes

Parameters

$b^{\mathrm{TRA}}_{i,j,k,z}/b^{\mathrm{TRO}}_{i,j,o,z}$	If the route is available to transport oil product k/oil products of type o from refinery i to depot j by mode z
$b^{\mathrm{O}}_{k,o}$	If oil product k belongs to type o
$b^{\mathrm{R}}_{i,s}/b^{\mathrm{D}}_{j,s}$	If refinery i/depot j belongs to shipper s
$b^{\mathrm{RC}}_{i,k}$	If refinery i can supply oil product k to depots belonging to different shippers
$b^{\mathrm{DC}}_{j,k}$	If depot j can receive oil product k from refineries belonging to different shippers
$c^{\mathrm{RS}}_{i,k}$	Unit loss caused by backlog of oil product k of refinery i (CNY/t)
$c^{\mathrm{DS}}_{j,k}$	Unit loss caused by stockout of oil product k of depot j (CNY/t)
$c^{\mathrm{TRA}}_{i,j,k,z}$	Unit freight to transport oil product k from refinery i to depot j by mode z (CNY/(t·km))
$c^{\mathrm{PC}}_{i,k,c}$	Oil substitution cost c of oil product k of refinery i (CNY/t)
fso_s	Basic cost of shipper s (CNY)
fco_z	Basic revenue of carrier z (CNY)
$l^{\mathrm{TRA}}_{i,j,z}$	The distance from refinery i to depot j by mode z (km)
M	A large constant
$q^{\mathrm{RE,min}}_{i,k}/q^{\mathrm{RE,max}}_{i,k}$	Lower/Upper supply volume of oil product k of refinery i (t)
$q^{\mathrm{DE,min}}_{j,k}/q^{\mathrm{DE,max}}_{j,k}$	Lower/Upper demand volume of oil product k of depot j (t)
$q^{\mathrm{RC,max}}_{i,k}$	Upper volume of oil product k supplied from refinery i to depots belonging to different shippers (t)
$q^{\mathrm{DC,max}}_{j,k}$	Upper volume of oil product k received from refineries belonging to different shippers to depot j (t)
$r^{\mathrm{PT}}_{z,a}$	Freight adjustment factor a of carrier z
$v^{\mathrm{TRA,min}}_{i,j,k,z}/v^{\mathrm{TRA,max}}_{i,j,k,z}$	Lower/Upper capacity to transport oil product k from refinery i to depot j by mode z (t)
$v^{\mathrm{TRO,min}}_{i,j,o,z}/v^{\mathrm{TRO,max}}_{i,j,o,z}$	Lower/Upper capacity to transport oil products of type o from refinery i to depot j by mode z (t)
y^{min}_e/y^{max}_e	Lower/Upper value of revenue-added interval e (CNY)
α_s/β_z	Bargaining power of shipper s/carrier z
ε_e/θ_e	Linearized parameters in revenue-added interval e

Variables

$BS_{s,e}/BC_{z,e}$	If added revenue of shipper s/carrier z is in interval e
$BPT_{z,a}$	If transportation freight a is selected by carrier z
$BPC_{i,k,c}$	If oil substitution cost c of oil product k is selected by refinery i
$C^{\mathrm{TC}}_{i,k}$	Unit substitution cost of oil product k for refinery i (CNY/t)
$PX^{\mathrm{TRB}}_{i,j,k,z}$	Linearization approximation of $R^{\mathrm{TR}}_z V^{\mathrm{TRA}}_{i,j,k,z}$
$PX^{\mathrm{TRC}}_{i,j,k,z}$	Linearization approximation of $C^{\mathrm{TC}}_{i,k} V^{\mathrm{TRA}}_{i,j,k,z}$
$Q^{\mathrm{RE}}_{i,k}$	Planned supply volume of oil product k of refinery i (t)
$Q^{\mathrm{DE}}_{j,k}$	Planned demand volume of oil product k of depot j (t)
$Q^{\mathrm{RC}}_{i,k}$	Oil product k supplied from refinery i to depots belonging to different shippers (t)
$Q^{\mathrm{DC}}_{j,k}$	Oil product k received from refineries belonging to different shippers to depot j (t)
$V^{\mathrm{TRA}}_{i,j,k,z}$	Oil product k transported from refinery i to depot j by mode z (t)
R^{TR}_z	Freight adjustment factor of carrier z
$S^{\mathrm{RE}}_{i,k}$	Backlog volume of oil product k of refinery i (t)
$S^{\mathrm{DE}}_{j,k}$	Stockout volume of oil product k of depot j (t)
FS_s/FC_z	Decreased cost of shipper s/Added revenue of carrier z (CNY)
$SCV_s/SCX_s/SCY_s$	Transportation cost/oil substitution cost/revenue of shipper s (CNY)
SCS_s	Penalty cost from supply and demand imbalances of shipper s (CNY)
YS_s	Linearization approximation of $\ln FS_s$
YC_z	Linearization approximation of $\ln FC_z$

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