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RESEARCH ARTICLE

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Sustainable refined products supply chain: A reliability assessment for demand-side management in primary distribution processes

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Abstract
The reliable operation of the primary distribution of refined products supply chains is crucial in guaranteeing the demand for retail markets. The uncertainties such as demand, production, and inventory will affect the supply chain operation. However, there lacks literature that studies the reliability of demand-side management of refined products supply chains. This reliability assessment can help define the weak points and boost the performance of the supply chain. And it can help decision-makers to improve the satisfaction of retail markets. In this paper, a systematic method for comprehensively assessing the reliability of refined products supply chains is proposed. At first, a mathematical programming model is developed to get the distribution plan of refined products. Then, several scenarios such as increasing demand, decreasing production, refineries disruption, and pipeline interruption relevant to the real situations of refined products supply chains are defined. Besides, indices including satisfaction rate, number of dissatisfied retail markets, refined products shortage, shortage of a single retail market, and average shortage duration are proposed to evaluate the reliability of the demand-side management in primary distribution processes. At last, the Monte Carlo simulation is adopted for a comprehensive analysis combining all the scenarios. This analysis shows a clear picture of the influence of uncertainties. This method is applied to assess the reliability of demand-side management of a real refined products supply chain. After analyzing different scenarios, the average probability of dissatisfaction under the reference scenario came as 1.93×10^{-4}/day that means one day in around 14.2 years could have refined products shortage. This method can also help decision-makers to assess other primary distribution of refined products supply chains.

KEYWORDS
demand-side management, primary distribution, refined products supply chain, reliability, scenario analysis

Abbreviations: MILP, Mixed-integer linear programming; PD, Primary distribution; RM, Retail market; RPSC, Refined products supply chain; SD, Storage depot.

1 | INTRODUCTION

With the rapid economic development, China has become the second-largest oil consumer in the world accounting for the consumption of around 12,799 thousand barrels of oil per day.[1] The major concern in the energy sector of China is the supply of oil[2] and China consumes 90% of the oil for petroleum-based production.[3] China's dependence on petroleum and its related products will maintain a stable increasing trend in the near future.[4] However, the refined products supply chain (RPSC) may suffer from various risks, including abnormal demand, production fluctuations, and refinery shutdown caused by natural disasters or human-induced disasters.[5] These types of uncertainties are almost inevitable, and they will impact the supply of refined products. It is crucial to ensure the safe and stable operation of the RPSC.

The reliability of the RPSC is a vital issue not only for the government to satisfy the demand of citizens and guarantee the production of industry, but also for the refined products sales company to be competitive.[6] Failures in any sector of an oil supply chain could cause a supply shortage.[3] Improving the reliability of the RPSC is vital to ensure the normal operation of oil depots and the normal supply of retail markets (RMs).[7,8] Accurate reliability evaluation and analysis of the RPSC system are of great practical significance for reducing system risks. There are mainly two aspects that will influence the operation of RPSCs, one is the fluctuation of demand and production,[9] and the other is the disruption of refineries, interruption of pipelines, and other huge accidents caused by natural disasters or human-induced incidences.[10] Considering these factors comprehensively, the evaluation of the reliability of the supply chain can be realized, which will help to understand the operational level of the supply chain and enhance emergency support.

In this paper, a framework for the reliability assessment for demand-side management of RPSC is proposed. A mathematical model is developed to simulate the distribution process of the RPSC. Several scenarios such as the demand increase, production decrease, disruption of refineries, and interruption of pipelines that relevant to the real situations of this supply chain are analyzed by this model. Then, Monte Carlo simulation that comprehensively considers these above scenarios with the probability is performed. Finally, the reliability-related indices can be calculated, and the reliability for demand-side management of an RPSC can be assessed.

This paper is organized as follows: Section 2 is the related work of this paper. Section 3 provides an overview of the proposed methodology. In Section 4, a mathematical model is developed for the simulation of the RPSC. We use this model to simulate the operation of RPSC and get the distribution plan. And we propose several indices and scenarios to analyze the RPSC from many aspects. A study case is described in Section 5, and the details of this supply chain are given. The results are discussed in Section 6. The conclusion is given in Section 7.

2 | LITERATURE REVIEW

With more concern about the safe and stable operation of the supply chain, the reliability has been receiving increasing attention in recent years. Hasan et al[11] provided a mathematical definition and relevant functions to apply the traditional reliability theory to the application of the supply chain reliability assessment. Jabbarzadeh et al[9] designed a supply chain considering the fortification investments when the supply/demand interruptions and facilities disruptions had impacts on the supply chain. Koleva et al[12] proposed a multi-objective mixed-integer linear programming (MILP) model for the design of a water supply chain. The objectives included minimizing the capital and operating expenditures and maximizing the reliability of the supply chain by quantifying how much of the demand will not be met. Snoeck et al[13] developed a methodology to evaluate the costs of disruptions and the value of supply chain network mitigation options of a chemical supply chain, and the supply risks were focused. Behdani et al[14] presented an agent-oriented simulation framework for disruption management in chemical supply chains. The model can help decision-makers to experience different types of disruption and disruption management strategies. Lin et al[15] developed a model to evaluate the reliability of the supply chain for brittle commodity logistics. In their study, the potential damages caused by natural disasters, traffic accidents, and collisions to the goods were considered. Current studies mainly considered reliability as one of the objectives in the design model and conducted discussions on the specific supply chain. However, the facilities in RPSCs are different from other supply chains, especially the transport mode of pipelines that other supply chains do not usually have. Besides, the causes that lead to unreliable situations are different from other supply chains. The production of refineries and the demand for depots are not stable and may cause an imbalance between these objects[9] Also, refineries may suffer from fully or partly disruption,[16,17] and the transportation process may be fully blocked by natural disasters[18] or other man-made accidents.[19] The probabilities of these unnormal situations are different from other supply chains, and we cannot migrate the results and data from other supply chains directly. Thus, it is important to develop a method for the quantitative evaluation of the reliability of RPSCs.

Apart from the applications of reliability in other industries, the reliability assessment has also aroused much attention in the oil and gas industry. Previous papers that studied the design and operation problems of oil and gas supply chains focused on reducing the cost.[20-22] Currently, how the existing transport system can meet the demand of markets and tackle abnormal situations becomes a more widely discussed issue. For the crude oil supply chain, Cigolini and Rossi[23] analyzed the risk from the drilling stage to the crude oil transport stage and the refining stage. Most of the studies focused on gas pipeline networks. Su et al[24] presented a systematic method for reliability assessment. They used a thermal-hydraulic calculation to simulate natural gas pipeline networks, the capacities of the pipeline network under different scenarios were calculated, and the consequences of failures of units were analyzed. Yu et al[25] developed a method to quantify the gas supply capacity of natural gas transmission pipeline systems. Later, Yu et al[26] proposed a methodology to assess the gas supply reliability. The demand for natural gas was predicted, and then, the Monte Carlo simulation was conducted to assess the gas supply reliability. Recently, Zhang et al[27] considered the hub disruption in the design of oil product supply chains. A multi-scenario MILP model coupled with Monte Carlo sampling was applied to solve the problem.

To access the reliability of an RPSC, some methodologies should be applied. Mathematical programming models are generally adopted to inform guidelines for real distribution plans and the solutions can be the fundament for the analysis. The facilities in the RPSC can be regarded as sets in the model, and the transport feasibility, material balance, and sending capacity in the RPSC can be modeled as constraints. In our study, we focus on the primary distribution (PD) part of the RPSC, and the process is started from the production in refineries, through the transportation to storage depots (SDs), and finally the distribution to local depots at RMs.

Researchers have done some relevant studies on the design and planning of the oil supply chain.[28-32] The mathematical models developed in their studies were used as efficient tools to determine the distribution plans. While some studies[33-36] applied sampling methods such as the Monte Carlo method to sample the uncertain data in the optimization of the oil supply chain, the above studies can be the references for our paper to develop the mathematical model that can optimize the distribution plan of the RPSC. Meanwhile, the Monte Carlo method is applied in this study to generate a large amount of sampling data as uncertain parameters in the RPSC for reliability assessment.

Therefore, according to our observations, most of the existing literature that studied the RPSC focused on design and planning, a few papers coupled the reliability in the planning process. However, whether an RPSC can meet the demand of RMs, how is the probability of potential shortage, which component is the vulnerable part in the RPSC, how to improve the reliability of the RPSC still need to be studied. Hence, a systematic framework should be developed to assess the reliability of the PD of RPSCs that consider: a) the uncertain of demand, production, and inventory, b) the distribution plan of refined products, c) facilities and transport logistics, and d) possibilities that will lead to refined products shortage.

3 | FRAMEWORK OF THE RELIABILITY ASSESSMENT METHOD

To evaluate the reliability of demand-side management of the RPSC, a systematic method is developed. This method

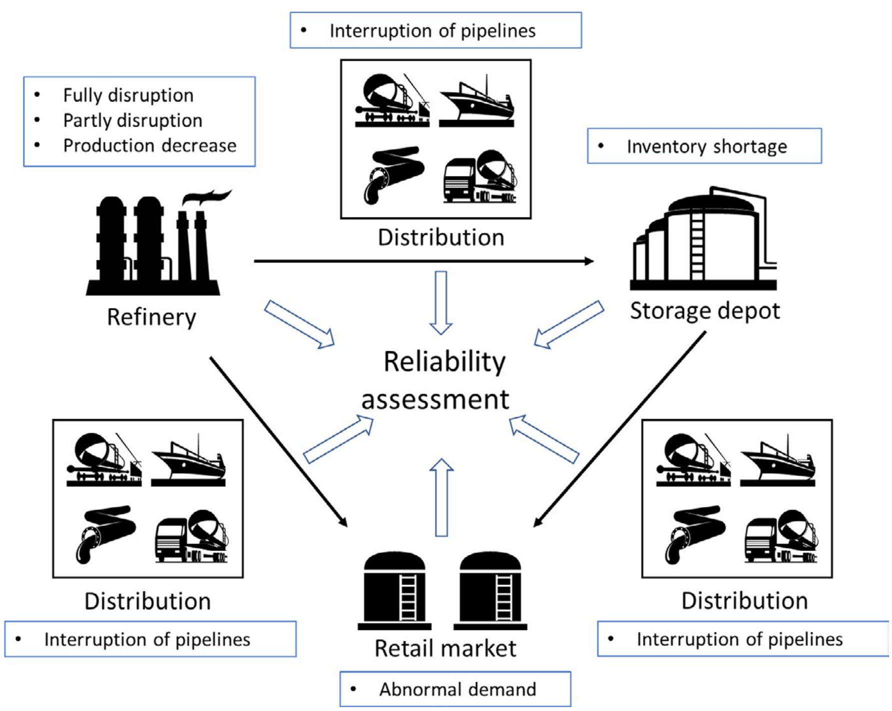

FIGURE 1 Reliabilities in the PD of RPSC. PD, Primary distribution; RPSC, Refined products supply chain

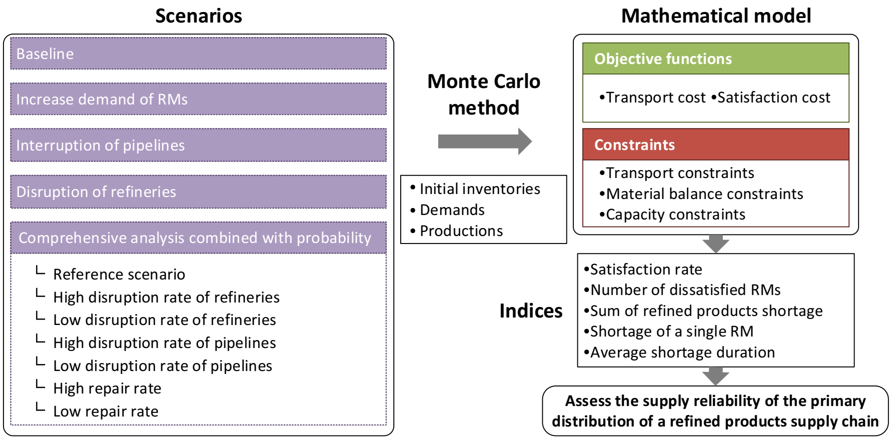

FIGURE 2 Framework of the proposed method

contains three parts, the first is the mathematical model, the second is the indices for supply chain assessment, and the last part contains several scenarios that help to analyze the RPSC from various aspects.

In the PD of an RPSC (Figure 1), it contains some facilities including refineries, oil depots, and RMs. Crude oil is processed into refined products in refineries. Then, the refined products can be transported to RMs through SDs and can be sent directly from the refineries to the RMs. In our case, we refer to the local oil depots as the RMs and neglect the secondary distribution which is started from the local depots. The main transport modes in the PD are railways, pipelines, waterways, and highways. Among them, the pipelines and railways play the main role.

In this system, each refinery, SD, and RM has depots. The volumes in these depots have their upper bounds and lower bounds. Also, the refined products can a) be transported from the refineries to RMs directly, and b) be transported from refineries and be stored in the SDs and then be transported to RMs from these SDs. The transport volume should not exceed the upper bound for each transport mode from refineries to SDs, from refineries to RMs and from SDs to RMs.

In this process, the unreliable situations may come from the abnormal demand, inventory shortage, the full and partial disruption of refineries, and the interruption of pipelines. The above situations may happen under some probabilities, and if they do not return to the normal condition timely, the shortage at the demand-side may occur.

The framework of this method is shown in Figure 2. First, a mathematical model is developed to simulate the distribution plans of the RPSC. The model contains the transport cost and satisfaction cost and has transport constraints, material balance constraints, and capacity constraints to make this model as real as the actual distribution process. The model can determine how much refined products should be transported in each transport mode from each refinery to each RM. The solved results can serve as the fundament for the follow-up analysis. Because the RPSC has several unnormal situations, to evaluate the influence of these situations, several scenarios are proposed including baseline, increase demand for RMs, interruption of pipelines, disruption of refineries, and comprehensive analysis. These scenarios will be solved by the mathematical model to get their distribution plans. The baseline is used to show the distribution results when the studied RPSC is operating under normal condition. The second to fourth scenarios are used to assess the effects of these single unnormal situations on the operation of RPSC. The comprehensive analysis is used to simulate the operating of an RPSC considering all these scenarios simultaneously in a certain time period. The initial inventories, demands, and productions data of each day in a 60-day time horizon are generated by the Monte Carlo method, and the mathematical model is applied to solve the daily distribution plan. The inventory of the simulation of the last day will be input as the parameter of the simulation of the current day. Then, we can observe the simulation results of each day to evaluate the reliability of the RPSC. For better reliability analysis, several indices are proposed including the satisfaction rate, number of dissatisfied RMs, amount of refined products shortage, shortage of a single RM, and average shortage duration. These indices can be calculated according to the results solved by the mathematical model. The reliability of the PD of an RPSC can be assessed by analyzing these indices.

4 | DETAILS OF METHOD IMPLEMENT

4.1 | Mathematical model

A mathematical model is developed to describe the process of the PD of the RPSC. This mathematical model aims to minimize transport cost and satisfaction cost.

Given the following inputs: (a) geographical distribution of refineries, SDs, and RMs; (b) refined products demand of RMs over a fixed time horizon; and (c) transport logistics (modes, capacities, distances, availability, and costs). The key variables to be solved are the distribution plan for refined products to be sent to RMs and the total costs for the PD of the RPSC.

4.1.1 | Objective function

$$f = \mathrm{CTR} + \mathrm{CTD} + \mathrm{CTC} + \mathrm{CV} \tag{1}$$

$$\mathrm{CTR} = \sum_{p\in P}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R}\sum_{t\in T} \mathrm{XR}_{p,i,j,r,t}\mathrm{TOR}_{p,i,j,r,t} \tag{2}$$

$$\mathrm{CTD} = \sum_{p\in P}\sum_{i\in I}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} \mathrm{XD}_{p,i,k,r,t}\mathrm{TOD}_{p,i,k,r,t} \tag{3}$$

$$CTC = \sum_{p\in P}\sum_{j\in J}\sum_{k\in K}\sum_{r\in R}\sum_{t\in T} XC_{p,j,k,r,t}TOC_{p,j,k,r,t} \tag{4}$$

$$\mathrm{CV} = \sum_{p\in P}\sum_{k\in K}\sum_{t\in T}\left(\delta\frac{\mathrm{VA}_{p,k,t}}{D_{p,k,t}}\right)^{a} \tag{5}$$

The objective function (1) minimizes the total transportation cost and satisfaction cost and has four parts. The former three parts are the transportation cost from refineries to SDs, from SDs to RMs and from refineries to RMs, respectively. The fourth part is the satisfaction cost; it describes the relationship between shortage and demand of the RMs. The detail calculation equations are listed in Constraints (2)-(5). In Constraint (5), δ is the unit satisfaction cost, and a is a coefficient that describes the relationship between the percentage of shortage and the satisfaction rate, which is selected as 1 or 2 in the model.

There are two situations for the satisfaction rate, linear, and nonlinear. When the satisfaction rate is linear (ie, a = 1), the satisfaction rate equals to the difference of demand and shortage of all RMs divided by the demand of all markets. In this case, no matter where the shortage happens, the satisfaction rates are the same, and it is only related to the total shortage amount. However, when a = 2, the effect of shortage in every RM will be enhanced. For example, if the total shortage amount is fixed, then the minimum satisfaction rate can be gotten when the shortage of all the markets are evenly distributed. This can help to reduce the chance that some RMs have severe shortages. These two options of satisfaction rate are tested to evaluate which one is suitable to work as an index in the reliability assessment.

4.1.2 | Material balance constraints

$$\mathrm{VR}_{p,i,t} = \mathrm{VR}_{p,i,t-1} + \mathrm{VPR}_{p,i,t} - \sum_{j\in J}\mathrm{XR}_{p,i,j,r,t} - \sum_{k\in K}\mathrm{XD}_{p,i,k,r,t}, \forall p\in P, i\in I, r\in R, t\in T, t>t_1 \tag{6}$$

$$\mathrm{VR}_{p,i,t} = \mathrm{ISR}_{p,i} + \mathrm{VPR}_{p,i,t} - \sum_{j\in J}\mathrm{XR}_{p,i,j,r,t} - \sum_{k\in K}\mathrm{XD}_{p,i,k,r,t}, \forall p\in P, i\in I, r\in R, t=t_1 \tag{7}$$

Constraints (6) and (7) are the material balance constraints for refineries. The volume for the product p at the refinery i in the period of t equals the volume in the period of t-1 plus the production and minus the volume transported to SDs and RMs. In the first period, the volume equals the initial stock of product p at refinery i plus the production and minus the volume transported to SDs and RMs.

$$\mathrm{VD}_{p,j,t} = \mathrm{VD}_{p,j,t-1} + \sum_{i\in I}\mathrm{XR}_{p,i,j,r,t} - \sum_{k\in K}\mathrm{XC}_{p,j,k,r,t}, \forall p\in P, j\in J, r\in R, t\in T, t>t_1 \tag{8}$$

$$\mathrm{VD}_{p,j,t} = \mathrm{ISD}_{p,j} + \sum_{i\in I}\mathrm{XR}_{p,i,j,r,t} - \sum_{k\in K}\mathrm{XC}_{p,j,k,r,t}, \forall p\in P, j\in J, r\in R, t=t_1 \tag{9}$$

Constraints (8) and (9) are material balance constraints for SDs. The volume for the product p at the SD j in the period of t equals the volume in the period of t-1 plus the volume sent from refineries and minus the volume transported to RMs. In the first period, the volume equals the initial stock of the product p at the SD j plus the volume sent from refineries and minus the volume transported to RMs.

$$\mathrm{VC}_{p,k,t} = \mathrm{VC}_{p,k,t-1} + \sum_{j\in J}\mathrm{XC}_{p,j,k,r,t} + \sum_{i\in I}\mathrm{XD}_{p,i,k,r,t} - (D_{p,k,t} - U_{p,k,t}), \forall p\in P, k\in K, r\in R, t\in T, t>t_1 \tag{10}$$

$$\mathrm{VC}_{p,k,t} = \mathrm{ISC}_{p,k} + \sum_{j\in J}\mathrm{XC}_{p,j,k,r,t} + \sum_{i\in I}\mathrm{XD}_{p,i,k,r,t} - (D_{p,k,t} - U_{p,k,t}), \forall p\in P, k\in K, r\in R, t=t_1 \tag{11}$$

Constraints (10) and (11) are material balance constraints for RMs. The volume for the product p at the RM k in the period of t equals the volume in the period of t-1 plus the volume sent from refineries and the SDs and minus the consumption of the RM k. For the first period, the volume equals the initial stock of the product p at the RM k plus the production sent from refineries and SDs, then minus the consumption of the RM k. The consumption of the RM equals the demand minus the shortage.

4.1.3 | Capacity constraints

$$\mathrm{MinVR}_{p,i} \le \mathrm{VR}_{p,i,t} \le \mathrm{MaxVR}_{p,i}, \forall p\in P, i\in I, t\in T \tag{12}$$

$$\mathrm{MinVD}_{p,j} \le \mathrm{VD}_{p,j,t} \le \mathrm{MaxVD}_{p,j}, \forall p\in P, j\in J, t\in T \tag{13}$$

$$\mathrm{MinVC}_{p,k} \le \mathrm{VC}_{p,k,t} \le \mathrm{MaxVC}_{p,k}, \forall p\in P, k\in K, t\in T \tag{14}$$

Refineries, SDs, and RMs have their inventory capacities. Constraints (12)–(14) ensure that the inventory levels of all these facilities should not exceed their inventory capacities and should not be lower than their minimum inventory volumes.

$$\mathrm{XR}_{p,i,j,r,t} \le \mathrm{MaxXR}_{p,i,j,r,t} \times \mathrm{BR}_{p,i,j,r,t}, \forall p \in P, i \in I, j \in J, r \in R, t \in T \quad (15)$$

$$\mathrm{XD}_{p,i,k,r,t} \le \mathrm{MaxXD}_{p,i,k,r,t} \times \mathrm{BD}_{p,i,k,r,t}, \forall p \in P, i \in I, k \in K, r \in R, t \in T \quad (16)$$

$$\mathrm{XC}_{p,j,k,r,t} \le \mathrm{MaxXC}_{p,j,k,r,t} \times \mathrm{BC}_{p,j,k,r,t}, \forall p \in P, j \in J, k \in K, r \in R, t \in T \quad (17)$$

Each transport mode has its transport capacity. There are three types of transport routes, 1) from refineries to SDs, 2) from refineries to RMs, and 3) from SDs to RMs. $\mathrm{BR}_{p,i,j,r,t}$, $\mathrm{BD}_{p,i,k,r,t}$, and $\mathrm{BC}_{p,j,k,r,t}$ are 0-1 parameters that record the feasibility of the transport. Constraints (15)–(17) ensure that the volume of product p transported by transport mode r in period t for every transport route should not exceed the maximum transport capacity.

$$\sum_{j \in J} \mathrm{XR}_{p,i,j,r,t} + \sum_{k \in K} \mathrm{XD}_{p,i,k,r,t} \le \mathrm{MaxSR}_{p,i,r,t}, \forall p \in P, i \in I, r \in R, t \in T \quad (18)$$

$$\sum_{k \in K} \mathrm{XC}_{p,j,k,r,t} \le \mathrm{MaxSD}_{p,j,r,t}, \forall p \in P, j \in J, r \in R, t \in T \quad (19)$$

Refineries and SDs have their sending capacities for each type of transport mode. Constraints (18) and (19) are used to limit the sending volume of refineries, and SDs are in their maximum sending capacity.

$$\mathrm{MinPR}_i \le \sum_{p \in P} \sum_{j \in J} \mathrm{XR}_{p,i,j,r,t} + \sum_{p \in P} \sum_{k \in K} \mathrm{XD}_{p,i,k,r,t} \le \mathrm{MaxPR}_i, \forall i \in I_S, r \in R_P, t \in T \quad (20)$$

$$\mathrm{MinRD}_j \le \sum_{p \in P} \sum_{k \in K} \mathrm{XC}_{p,j,k,r,t} \le \mathrm{MaxRD}_j, \forall j \in J_S, r \in R_P, t \in T \quad (21)$$

Constraints (20) and (21) ensure that each pipeline has its maximum and minimum transport capacity. In Constraint (20), the amount of transported refined products in the pipeline that started from the refinery i and linked to several SDs and RMs should be lower than the maximum transport capacity and be higher than the minimum transport capacity of that pipeline. Constraint (21) means that the pipeline started from the SD j also has its maximum and minimum transport capacity.

4.2 | Assessment indices

Reliability assessment of demand-side management in a RPSC consists of two aspects: global and individual. The global aspect represents the functional integrity of the supply chain; the individual aspect reflects the ability of the supply chain to satisfy the demand of a single RM. The supply chain aims to serve the RMs stably and continuously. However, considering the differences among individual refined products demand, the fluctuation of supply and demand, and the disruption of refineries and transport facilities, the RPSC may not be able to satisfy all RMs under all conditions. In other words, the satisfied demand for RMs can vary. Thus, we have to propose several indices including (1) satisfaction rate, (2) indices for global reliability, (3) the shortage of a single RM, and (4) the average shortage duration, to assess the supply chain reliability.

4.2.1 | Satisfaction rate

The main task of operating an RPSC is to ensure the RMs can have enough refined products transported from their upstream facilities. To evaluate the working performance of this task, the satisfaction rate is proposed. It is the value of the actual received amount divided by the demand of all the RMs, and we use the following formula to calculate.

$$\text{Satisfaction rate} = \sum \left(\frac{\text{Demand of DMs} - \text{Shortage of DMs}}{\text{Demand of DMs}} \right)^a \quad (22)$$

where a is a coefficient that describes the relationship between the percentage of shortage and the satisfaction rate.

4.2.2 | Indices of global reliability

For the global reliability assessment, two indices are proposed. The first is the number of dissatisfied RMs, which indicates the number of RMs that their demands cannot be fully met when the shortage happens. The second index is the sum of the shortage of refined products. It indicates the total amount of shortage of all RMs when the shortage happens.

4.2.3 | The shortage of a single RM

The shortage amount of each RM in RPSCs can be different when the shortage happens. An index of the shortage of a single RM is proposed to describe the daily shortage of a single RM.

4.2.4 | The average shortage duration

Also, an index of the average shortage duration is proposed to describe the duration time when the shortage happens. The duration time is used to count the number of days when one or more RMs meet the shortage of refined products until all the RMs are satisfied.

4.3 | Scenario definition

The PD of the RPSC involves a broad variety of facilities, such as refineries, SDs, RMs, and four transport modes. These facilities have some probabilities of meeting full disruption or partial failure. Considering the real situation of the RPSC, some scenarios are introduced including: (1) baseline, (2) increase demand for RMs (IDR), (3) disruption of refineries (DR), (4) interruption of pipelines (IP), and (5) the comprehensive analysis combined with the probability (CAP).

4.3.1 | Baseline

This scenario is simulated to create a baseline for comparisons with other scenarios. In this scenario, all exogenous variables are fixed: the demand for RMs and the production rate of refineries. The volume in all depots is set as 0 to eliminate the influence of the inventory. There is no full or partial disruption in this scenario; all the facilities operate well. This scenario is used to determine the unit satisfaction cost in the proposed model and show the distribution results when the studied RPSC is operating under normal conditions.

4.3.2 | Increase demand for RMs (IDR)

IDR refers to the situation that the demand of RMs has exceeded the current projected demand. Demand growth is generally caused by two reasons. One is seasonal changes, for example, when winter comes, due to heating, antifreeze, and other needs, the demand for refined products increased sharply.[37] The other reason for the sudden increase in one or more RMs is due to situations such as a sudden increase in demand for industrial users or the fear of oil shortage. When these situations happen, the supply and demand cannot be matched. Meanwhile, refined products sales companies generally distribute refined products according to the criterion of maximum regional satisfaction from the perspective of the overall supply. Therefore, when the demand for a city suddenly increases, the shortage may appear in many cities. Because the amount of refined products transported to the city that has demand increment will be increased to prevent the shortage situation from getting worse.

4.3.3 | Disruption of refineries (DR)

The refinery is important but also a vulnerable part of the PD of RPSC.[38] It is responsible for the production of oil products required by each RM. The reasons for the supply disruption in refineries may come from the suspension of production in the upstream oilfields, the interruption of crude oil transportation,[39] or sudden accidents at the refineries.[17] The disruption of the refinery supply has a greater impact,it will lead to the situation of less production. However, consumption is continuing, which leads to the unbalance of supply and demand. Meanwhile, when a refinery is at a disruption situation, it also has the chance to return to normal.

4.3.4 | Interruption of pipelines (IP)

The pipeline is an important way to transport refined products, but it also can be interrupted by the following causes: mechanical, operational, corrosion, natural hazards, and third-party activity.[40] The pipeline is not like the railways or roads,there is no other alternative routes for the pipelines. When an accident occurs in a pipeline, such as the whole line shutting down, it will easily affect the refined products transportation. Similar to the refinery, the problems of the pipeline can be fixed, and it can resume transport.

4.3.5 | The comprehensive analysis combined with the probability (CAP)

In real RPSC, the emergence of the above scenarios has a certain probability. Analyzing the demand satisfaction of the RPSC combined with the probability of failure can help understand the reliability of the supply chain.

4.4 | Study case

In this section, a regional RPSC will be studied for reliability analysis. The study area is located in southwest China. To facilitate the discussion, we use R to represent refinery, SD to represent storage depot and C for RM.

There are 31 RMs with oil depots responsible for the secondary distribution of refined products to all cities in this region. The refined products are produced in four refineries, named R1 to R4. Also, there are four SDs in this area. Some of the refineries have their affiliated SDs for receiving refined products and then distributing to the depots of RMs. In this case, three SDs named SD1, SD2, and SD3 are next to refinery R2, R1, and R3, respectively, and there are pipelines built from corresponding refineries to these three SDs. Also, SD4 is a SD at the riverside. Refined products can be transported from this SD through waterway and highway to the RMs. RMs named C24, C25, C26, C27, and C28 in this area do not have the ability of railway unloading. They can only receive refined products from the waterway and highway.

In this region, there is a main pipeline for refined products transportation. The pipeline starts from R1, through SD2, connecting C1, C4, C5, C8, C11, C12, C16, C19, C23, C30, and SD4. To ensure the safe and economic operation of the pipeline, the pipeline has a minimum throughput.[41,42] Thus, it is assumed that if the flowrate is below the minimum throughput, the pipeline will not operate.

The tables in Appendix A show the details of this case. Table A1 shows the average daily demand of each RM. Table A2 shows the average daily production of each refinery. Table A3 and Table A4 show the maximum sending capacity of refineries and SDs. A simple sketch map of this area is shown in Figure 3.

5 | DISCUSSION

In this section, firstly we evaluate the relationship between the transport cost and satisfaction cost to find a suitable unit satisfaction cost that has little influence on the transport cost. Then, we simulate a set of scenarios to analyze the influence of facilities in the RPSC. Lastly, a comprehensive reliability analysis is performed to assess the performance of the PD of this RPSC.

5.1 | Analysis of baseline

In the baseline, we assume that the inventory of all the oil depots is not consumed, that is, the demand of RMs is ensured by the daily output of refineries. By solving the model under this assumption, we can get the distribution plan of refined products under the baseline. The distribution plan is shown in Figure 4.

Because the objectives of the model have both transportation cost and the satisfaction cost, to eliminate the impact of the satisfaction cost to the distribution plan, we have to try different unit satisfaction cost parameters to find the suitable one. The influence is reflected in two aspects, one is the transportation cost, and the other is the way of transportation. Taking the above two indicators as the test standard, we calculate several unit satisfaction cost parameters and try to find a suitable value as the parameter for the unit satisfaction cost. We use the baseline to test this unit cost.

Figure 5 shows the relationship among the unit satisfaction cost, total transport cost, and daily average satisfaction rate. When the unit satisfaction cost is low, it will occupy the dominant position in the whole system, which sacrifice the satisfaction of RM demand and reduce transportation cost to achieve the purpose of reducing the overall costs. However, when the value of unit satisfaction cost is higher, the transportation cost will grow up. The impact of unit satisfaction cost on transport cost is becoming smaller. We can observe that when the unit satisfaction cost is 1×10^9 yuan, the satisfaction cost has little effect on transport. With the rise of unit satisfaction cost, the transport cost is remaining stable at a value. We also compare two situations; the first one only has the transport cost in the objective model, and the results of the transport plan are shown in Table B1 of Appendix B. The second situation has both the transport cost and satisfaction cost. When the unit satisfaction cost is 1×10^9 yuan, the transport plan is shown in Table B2 of Appendix B.

Comparing with Table B1 and Table B2, we find that when the cost of satisfaction is set at 1×10^9 yuan, the

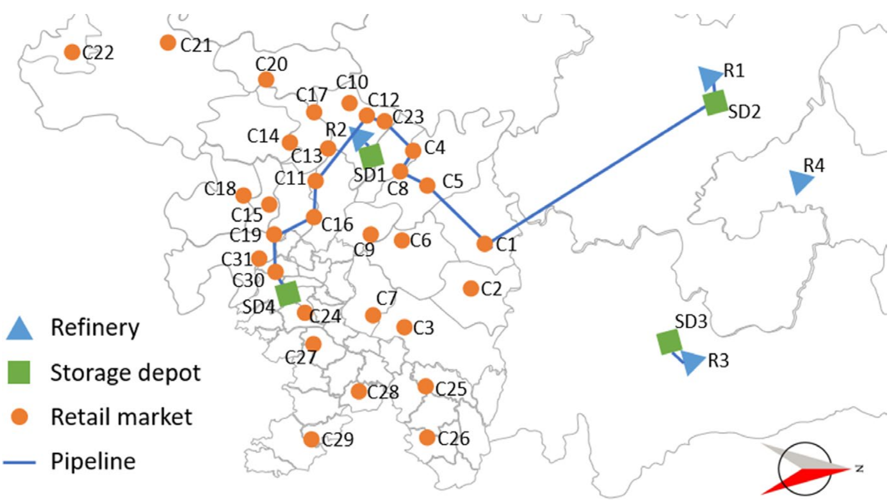

FIGURE 3 Simple sketch map of the study area

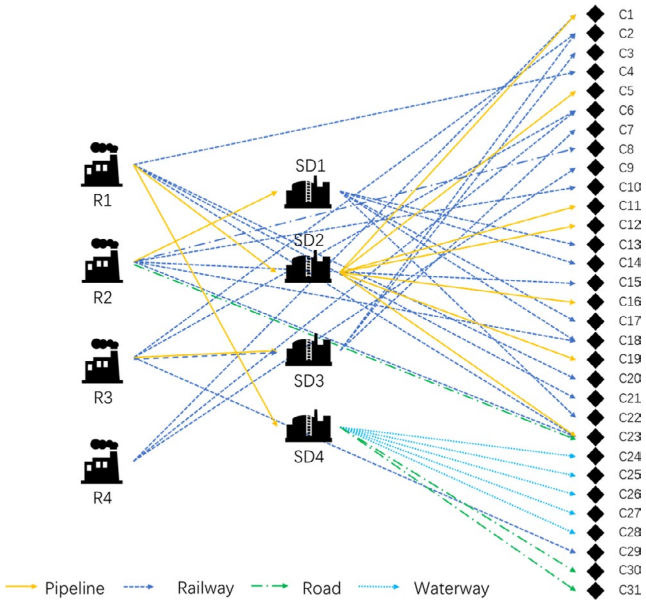

FIGURE 4 Distribution plan under the baseline

source of the refined products of each RM is the same for both situations, and the volume of oil transported through each transport mode only change very little. Therefore, it is reasonable to set the satisfaction cost of our follow-up study as 1×10^9 yuan.

5.2 | Analysis of DR

An important index to test the reliability of the regional RPSC is the supply security of RMs when all the refineries are completely disrupted. In our case, we analyze the following situation. We assume that all the depots of refineries, SDs, and RMs are all at their highest inventory volume. The refineries are completely disrupted, and the demand of each RM remains the same. We draw two curves of satisfaction rate under different satisfaction coefficient of Equation (22) in Figure 6, to show the transport cost and satisfaction rate at different disruption times.

As can be seen from the above chart, when the number of days of disruption is more than 8, some RMs cannot meet the demand by their inventories. In this situation, the transport cost starts to rise. Refined products are transported from the depots of refineries and SDs. Starting from the eighth day, the transportation cost of refined products increased rapidly, but the satisfaction rate does not decline, indicating that refineries and SDs have enough refined products inventory to satisfy the demand of RMs in these days. When the duration of disruption is greater than 29 days, there are some RMs whose demand cannot be met. At this point, the shortage happens. With the increase of outage days, the shortage begins to be distributed throughout the whole planning period. When the total days of disruption continue to grow, the transport cost will fluctuate, which is because of the minimum throughput of pipelines. The model is based on the objective of minimizing the total transportation cost in all the time of disruption. According to the characteristic of pipeline transportation, only when the transportation volume of the pipeline exceeds the minimum volume in some days can the pipeline be used as a more economical way of transportation. In some days, the volume of refined products that needed to be transported might be lower than the minimum throughput of the pipeline, then refined products will be transported by railways and other modes, and the cost increased.

An example that the total disruption time is 60 days is studied to observe the transportation costs and inventories. This case is analyzed when the satisfaction coefficient is equal to 2. Figure 7 shows the inventory from the first day when the disruption is started to the end of the whole period. Figure 8 shows the transport costs from refineries to SDs, SDs to RMs, and refineries to RMs.

As can be seen from Figure 7, the inventory of refineries and SDs remain unchanged in the first few days, and the

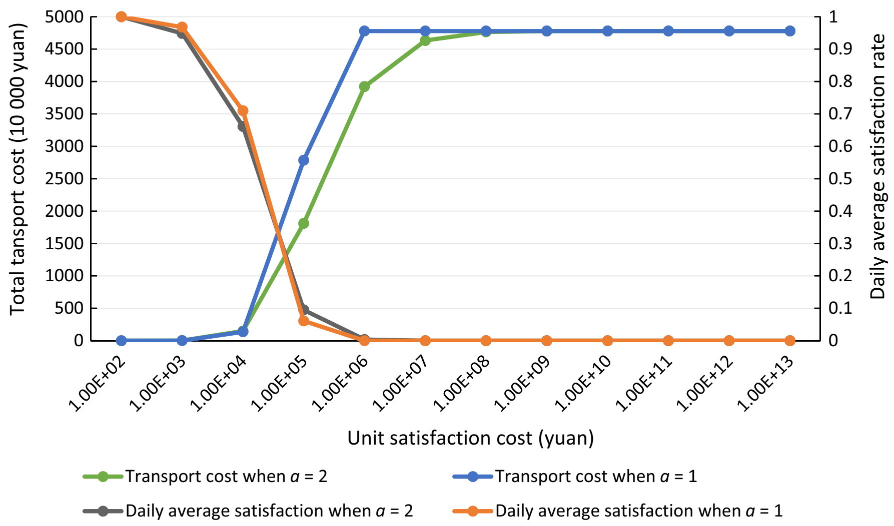

FIGURE 5 The relationship among the unit satisfaction cost, total transport cost, and daily average satisfaction rate

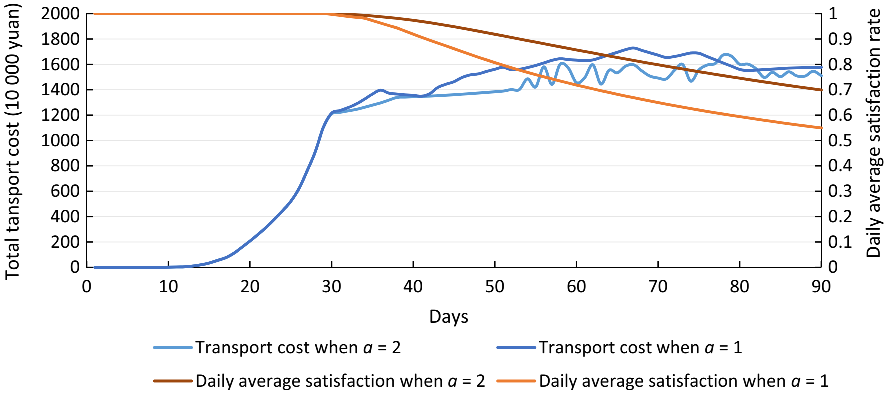

FIGURE 6 The relationship among the disruption days, total transport cost, and daily average satisfaction rate when the refineries are disrupted

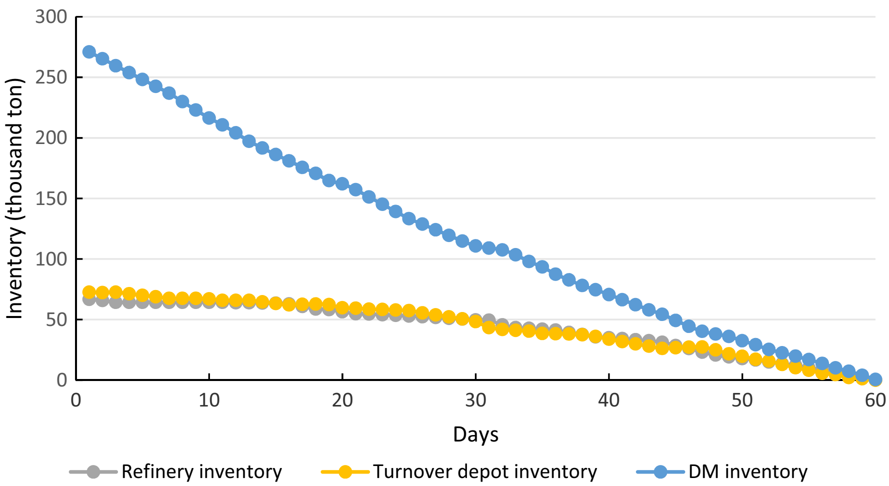

FIGURE 7 Inventory from the first day when the disruption is started to the end of the whole period

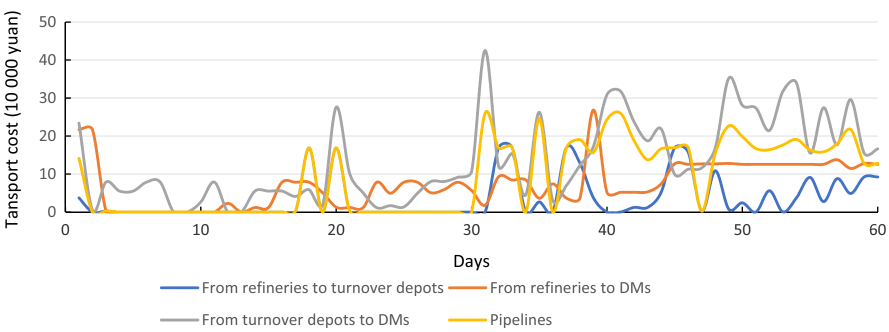

FIGURE 8 Transport costs of each day when the disruption time is 60 days

demand for RMs is satisfied by their inventories. Later, the depots of refineries distribute refined products to SDs and RMs, and SDs also supply RMs to meet their needs. The inventories of refineries and SDs decrease. According to the simulation result, when the shortage is more than 29 days, the demand cannot be satisfied. For this case of 60 days disruption, on the last day, the inventory of various oil depots comes to zero to maximize the satisfaction of all RMs.

According to the above discussion, at the initial stage, the main source of refined products is from the inventory of RMs, thus, as can be seen from Figure 8, the transport cost is relatively low. In the later stage, the initial inventory in the depots of RMs is used up. The refineries and SDs need to supply refined products to RMs, so transportation costs began to rise. Because the pipeline has the minimum throughput, the pipeline is usually operated intermittently, and the cost presents as a peak in some days.

When the refinery is partial failed, the production rate will decrease. Figure 9 describes the relationship among the decline in refinery production, transportation cost, and satisfaction rate. The capacity of all the refinery drops from 100% to 0%. In this case, we also assume that the inventory of each oil depot is 0 in a 30-day time horizon. When the refinery production capacity is normal, the demand for each RM can be satisfied. However, with the decline of the production of refineries, the amount of refined products that can be transported also decreases, as well

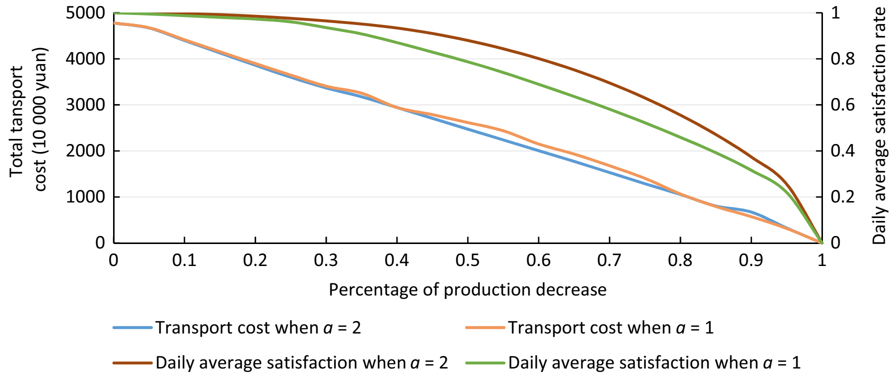

FIGURE 9 The relationship among the percentage of production decrease, total transport cost, and daily average satisfaction rate when the production of refineries decrease

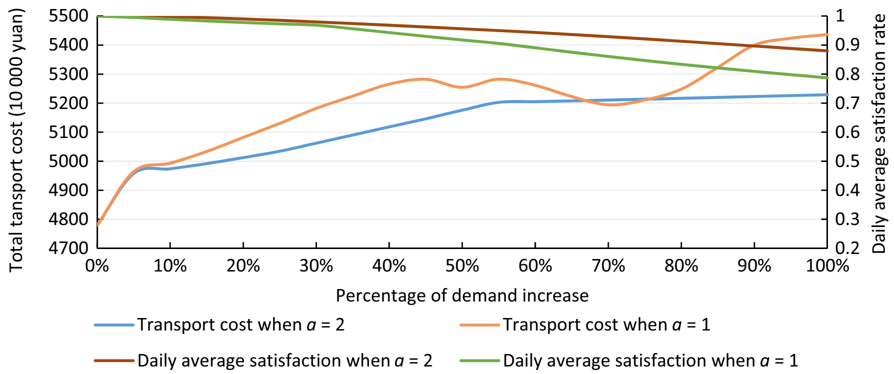

FIGURE 10 The relationship among the percentage of demand increase, total transport cost, and daily average satisfaction rate when the demand for RMs increases. RMs, Retail markets

as the transportation cost. When the refinery is completely disrupted, the demand of all RMs cannot be met.

5.3 | Analysis of IDR

Figure 10 describes the transportation cost and satisfaction rate when the demand for RMs increases (from 100% to 200%). In this scenario, we assume that all the oil depots have no inventory, and the sources of all RMs are refineries. As seen in Figure 10, when demand rises, transportation cost also rises and tends to be stable, which is related to the total production constraints. The average satisfaction rate reaches the minimal value in this case when the demand reaches 200% of the original demand.

5.4 | Analysis of IP

Figure 11(A) and Figure 11(B) show the amount of refined products received by each RM when pipelines are operating and when pipelines are all shut down in 30 days. In this scenario, we assume that all the oil depots have no inventory, and the sources of all RMs are refineries. As seen in these two figures, when pipelines are fully interrupted, the demand of many RMs cannot be satisfied. The existing rail and road sending capacity of some refineries and SDs cannot fully supplement the capacity of pipelines. Thus, it is important to ensure the safe operation of these pipelines to enhance the reliability of this RPSC.

5.5 | Comprehensive reliability analysis of RPSC

In a real PD process of an RPSC, there is a certain probability that the scenarios mentioned above will occur, and there is also a certain probability that the scenarios will return to normal. To analyze the reliability of the PD of the RPSC in the study region, we set up the following situation according to the reality.

5.5.1 | Initial stock

Considering the factors such as tank bottom oil, the inventory of refined products cannot be less than 30% of the total storage capacity and generally not more than 80% of the total storage capacity. For the initial inventory of each oil depot, we assume that it obeys the normal distribution, the mean inventory percentage is 50%, and the initial inventory percentage of each depot is between 30% and 70%.

5.5.2 | Production rate of refineries and demand of RMs

We assume that these two data also obey normal distribution. We select the daily average output and average daily consumption of refineries and RMs in this area as the mean value. The production rate of refineries fluctuates between

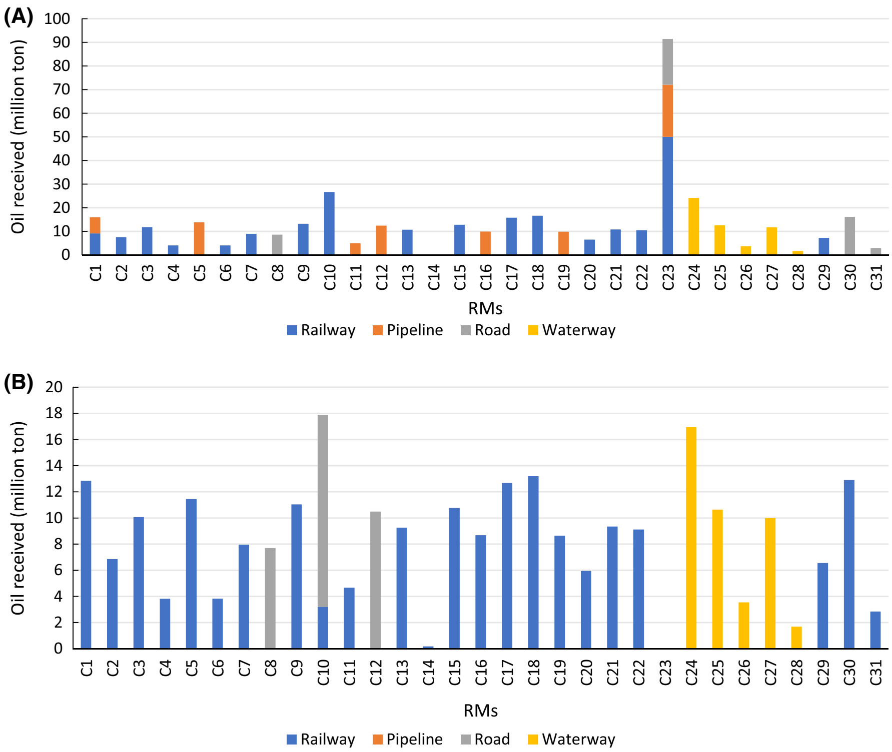

FIGURE 11 The amount of oil received by each RM for different pipeline condition. (A). The amount of oil received by each RM when pipelines are operating. (B). The amount of oil received by each RM when all pipelines are shutting down. RM, Retail market

95% and 105%, and the demand of RMs fluctuates between 80% and 120%.

5.5.3 | Disruption of refineries

There are two kinds of disruption, one is the complete shutdown of the refinery, which may happen due to natural disasters and other severe factors. The other is the partial failure of the refinery equipment. It will cause a decrease in production for the refineries. In our case, the probability of full refinery shutdown is 0.001 (/day), and the recovery rate is 0.25 (/day); the probability of partial disruption is 0.072 (/day), if a partial disruption accident happens, the production rate will drop to 50% of the normal production rate, and the recovery rate is 1 (/day).

5.5.4 | Interruption of pipelines

We set the corresponding probability of accidents for pipelines. If a major accident occurs in the pipeline, then the whole pipeline may be shut down. The accidents of the pipeline in our case from 2008 to 2018 is invested. The probability of a pipeline shutdown is 0.00274 (/day), and the recovery rate is 0.33 (/day).

According to the previous discussion, we use the Monte Carlo method to simulate the scenario in one hundred thousand times and 60 days per simulation.

The probabilities of shortage are shown in Figure 12(A). The date when the total shortage of RMs is more than 100 ton/day is counted. Each point in this figure represents a width of 50 tons/day. That means if the statistical data are within the range of each point, the corresponding probability will be added. From this figure, we can see that the highest consequence of refined products shortage is about 10 000 ton/day with the probability at around 10^{-5}. Most of the consequences are concentrated within the range of 0-7 500 ton/d, and the probability of more than half of the shortage is lower than 10^{-4}. The highest probability of shortage is 0.00028.

Also, in these simulations, a total of 1 158 days of unsatisfactory occurred, and 386 interruptions were recorded if a continuous interruption was considered as a single interruption. The shortest duration of these interruptions was one day, the longest duration was 16 days, and the average shortage duration is three days. For these interruptions, the minimum number of RMs that is dissatisfied is 1, the largest number is 30, and the average number of dissatisfied RMs is 27.73.

The average shortage of each RM is shown in Figure 12(B). And the total shortage and average shortage of RMs link to and not link to the pipeline are shown in Table 1. As we can see from Figure 12(B), the RM numbered C23 has the maximum shortage among all the RMs, more attention should be paid to guarantee its supply.

As can be seen from Table 1, the average shortage of RMs that link to the pipeline is larger than that of RMs not link to

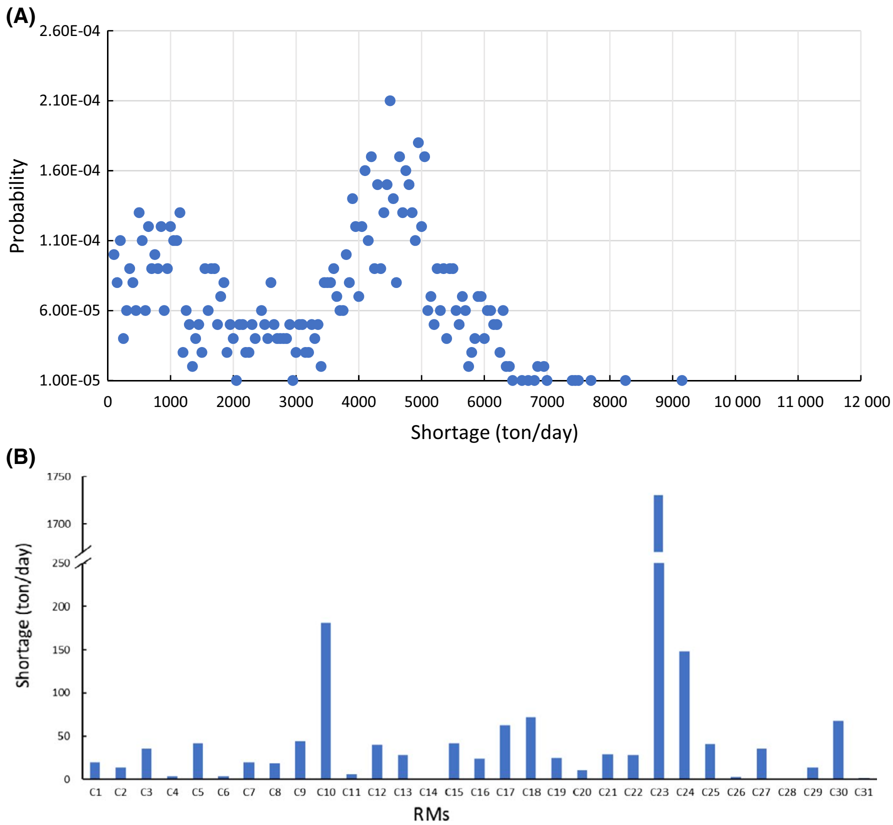

FIGURE 12 Shortage results in the comprehensive reliability analysis. (A). The probability of each amount of shortage. (B). The average shortage of each RM. RM, Retail market

TABLE 1 The total shortage and an average shortage of RMs

Indices	Amount (ton/day)
Total shortage	2 789.00
Shortage of RMs that link to the pipeline	1 975.75
Shortage of RMs that not link to the pipeline	813.25
Average shortage	89.97
Average shortage of RMs that link to the pipeline	197.57
Average shortage of RMs that not link to the pipeline	38.73

RMs, Retail markets.

the pipeline. Thus, the supply of pipeline should be particularly ensured, and emergency measures should be set up in case of pipeline interruption.

Because the value of failure and repair probability will have some impact on the results, so we test the reliability of the supply chain under different failure and repair probability scenarios, as shown in Table 2. For each scenario, we carry out 100 000 sets of calculations and simulate each of them for 60 days. The results are shown in Figure 13.

As we can see from Figure 13, when the failure probability of the refinery increases, the probability of each amount of shortages increases significantly. When the failure probability of the refineries decreases, the probability of each amount of shortages also decreases considerably. Also, the increase and decrease in the failure probability of the pipeline have little effect on the supply of the supply chain in this case. It is because when the pipeline fails, the refined products originally transported through the pipeline can be supplemented by other modes of transportation. Also, the repair probability has a great impact on the supply. When the repair probability is twice as large as the original, the probability of various shortages is significantly reduced. However, when the repair rate is reduced to half of the original figure, the probability of shortage increased tremendously. We can conclude that the failure rate and repair rate are both important to the reliability of demand-side management. If the disruption of the facilities in the supply chain can be repaired immediately, it will greatly ensure the reliability and avoid shortages.

6 | CONCLUSION

This study proposes a methodology to assess the reliability of the PD of RPSCs. A mathematical programming model is developed to simulate the RPSC. Several indices are proposed to evaluate the shortage situations, and scenarios are analyzed from the different aspects of the RPSC. The method is applied to a real RPSC in the southwest of China. The uncertain data in this case are sampled by the Monte Carlo method, and several scenarios related to the facilities in this supply chain are analyzed individually and comprehensively. We can conclude from this case in three main aspects. First,

TABLE 2 Scenarios of different probability rates

Scenarios	Description
Reference scenario	Failure and repair rates are the same as those described in Section 5.5.
High disruption rate of refineries	Full shutdown rate and partial disruption rate of refineries are 2 × 0.001/day and 2 × 0.0072/day; respectively, others are the same as the reference scenario.
Low disruption rate of refineries	Full shutdown rate and partial disruption rate of refineries are 0.5 × 0.001/day and 0.5 × 0.0072/day, respectively; others are the same as the reference scenario.
High disruption rate of pipelines	Full shutdown rate of pipelines is 2 × 0.00274/day; others are the same as the reference scenario.
Low disruption rate of pipelines	Full shutdown rate of pipelines is 0.5 × 0.00274/day; others are the same as the reference scenario.
High repair rate	The repair rate of recovery from the full shutdown of refineries, partial shutdown of refineries, and full shutdown of pipelines are 2 × 0.33/day, 1/day, and 2 × 0.25/day, respectively; others are the same as the reference scenario.
Low repair rate	The repair rate of recovery from the full shutdown of refineries, partial shutdown of refineries, and full shutdown of pipelines are 0.5 × 0.33/day, 0.5 × 1/day, and 0.5 × 0.25/day, respectively; others are the same as the reference scenario.

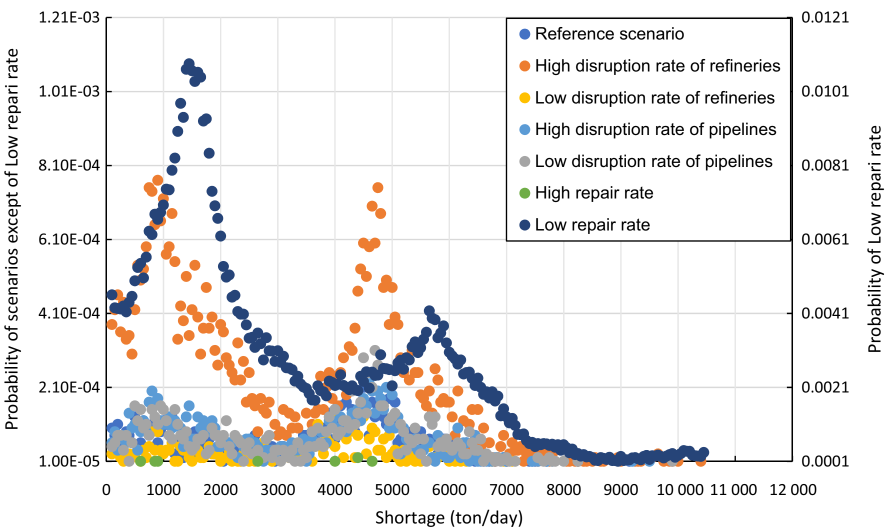

FIGURE 13 The shortage probability of each scenario

existing transport capacity and daily production capacity of the study case is sufficient to satisfy the daily demand of each RM even there is no inventory at depots. This means that the daily production and demand are balanced. Meanwhile, if the inventories of depots are full, it will help to meet the demand of RMs even the production is disrupted. Second, in the referenced scenario, 1,158 days of unsatisfactory occurred in a total of $10^5 \times 60$ days simulation, which means that the probability of dissatisfaction is 1.93×10^{-4}/day, which also means that one day in around 14.2 years could have refined products shortage. This is quite reliable for the PD of the RPSC. Third, the sensitivity analysis of the failure rate and repair rate shows that, in this case, it is important to guarantee the production of refineries. Also, it is more vital to reduce the repair time when the disruption happens, as it will greatly reduce the occurrence of demand imbalance. On the contrary, if a disruption cannot be fixed on time, it will lead to a shortage of RMs. Although the repair rate is only half of the normal level, the probability of dissatisfied increases an order of magnitude.

This method is also available to assess other RPSCs. The three-level of facilities in the model is general and realistic. The model can be modified according to the structure of the studied RPSCs. Transport modes can be adjusted according to the need. By calculating the proposed assessment indices in each scenario, the decision-makers can have an overview of the reliability of their studied RPSCs. It can also help decision-makers to have a better understanding of the RPSC operation, rank the importance of facilities in the RPSC, and identify RMs that might have the maximum shortage in accidents.

In the future, there are still many problems that need to be further studied. For example, how activities in the upstream oil supply chain will influence the reliability of the RPSC, how natural gas and biofuel will influence the demand side of the refined products and the RPSC should be studied.

ACKNOWLEDGMENT

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NOMENCLATURE

Indices and sets

I represents the set of refineries, denoted by index *i*.

J represents the set of SDs, denoted by index *j*.

K represents the set of RMs, denoted by index *k*.

P represents the set of types of refined product, denoted by index *p*.

R represents the set of transport modes, denoted by index *r*.

I_S represents the refineries that are also the start nodes of pipelines, $I_S \in I$.

J_S represents the SDs that are also the start nodes of pipelines, $J_S \in J$.

R_P represents the pipeline transport mode, $R_P \in R$.

T represents the set of time periods, denoted by index *t*.

Parameters

$TOR_{p,i,j,r,t}$ Unit cost of the product *p* transported from the refinery *i* to the SD *j* by the transport mode *r* in the time period *t*.

$TOD_{p,i,k,r,t}$ Unit cost of the product *p* transported from the refinery *i* to the RM *k* by the transport mode *r* in the time period *t*.

$TOC_{p,j,k,r,t}$ Unit cost of the product *p* transported from the SD *j* to the RM *k* by the transport mode *r* in the time period *t*.

$D_{p,k,t}$ Demand of the product *p* at the RM *k* in the time period *t*.

δ Unit satisfaction cost

a A coefficient that describes the relationship between the percentage of shortage and the satisfaction rate.

M A sufficiently large number

$BR_{p,i,j,r,t}$ Parameter equal to 1 if the product *p* can be transported from the refinery *i* to the SD *j* by the transport mode *r* in the time period *t* and 0 otherwise

$BD_{p,i,k,r,t}$ Parameter equal to 1 if the product *p* can be transported from the refinery *i* to the RM *k* by the transport mode *r* in the time period *t* and 0 otherwise

$BC_{p,j,k,r,t}$ Parameter equal to 1 if the product *p* can be transported from the SD *j* to the RM *k* by the transport mode *r* in the time period *t* and 0 otherwise

$VPR_{p,i,t}$ Production volume of the product *p* at the refinery *i* in the time period *t*.

$ISR_{p,i}$ Initial stock of the product *p* at the refinery *i*

$ISD_{p,j}$ Initial stock of the product *p* at the SD *j*

$ISC_{p,k}$ Initial stock of the product *p* at the SD *k*

$MinVR_{p,i}$ Minimum inventory volume for the product *p* stored at the refinery *i*

$MaxVR_{p,i}$ Maximum inventory volume for the product *p* stored at the refinery *i*

$MinVD_{p,j}$ Minimum inventory volume for the product *p* stored at the SD *j*

$MaxVD_{p,j}$ Maximum inventory volume for the product *p* stored at the SD *j*

$MinVC_{p,k}$ Minimum inventory volume for the product *p* stored at the RM *k*

$MaxVC_{p,k}$ Maximum inventory volume for the product *p* stored at the RM *k*

$MaxXR_{p,i,j,r,t}$ Maximum transport volume for the product *p* transported from the refinery *i* to the SD *j* by the transport mode *r* in the time period *t*.

$MaxXD_{p,i,k,r,t}$ Maximum transport volume for the product *p* transported from the refinery *i* to the RM *k* by the transport mode *r* in the time period *t*.

$MaxXC_{p,j,k,r,t}$ Maximum transport volume for the product *p* transported from the SD *j* to the RM *k* by the transport mode *r* in the time period *t*.

$MaxSR_{p,i,r,t}$ Maximum sending capacity for the product *p* transported from the refinery *i* by the transport mode *r* in the time period *t*.

$MaxSD_{p,j,r,t}$ Maximum sending capacity for the product *p* transported from the SD *j* by the transport mode *r* in the time period *t*.

$MaxPR_i$ Maximum transport capacity of the pipeline that is started from the refinery *i*

$MinPR_i$ Minimum transport capacity of the pipeline that is started from the refinery *i*

$MaxRD_j$ Maximum transport capacity of the pipeline that is started from the SD *j*

$MinRD_j$ Minimum transport capacity of the pipeline that is started from the SD *j*

Decision variables

CTR Transport cost from refineries to SDs.

CTD Transport cost from refineries to RMs.

CTC Transport cost from SDs to RMs.

CV Satisfaction cost

$XR_{p,i,j,r,t}$ Volume of the product *p* transported from the refinery *i* to the SD *j* by the transport mode *r* in the time period *t*.

$XD_{p,i,k,r,t}$ Volume of the product *p* transported from the refinery *i* to the RM *k* by the transport mode *r* in the time period *t*.

$XC_{p,j,k,r,t}$ Volume of the product *p* transported from the SD *j* to the RM *k* by the transport mode *r* in the time period *t*.

$VA_{p,k,t}$ Shortage of the product *p* at the RM *k* in the time period *t*.

$VR_{p,i,t}$ Volume of the product *p* stored at refinery *i* in the time period *t*.

$VD_{p,j,t}$ Volume of the product p stored at the SD j in the time period t.

$VC_{p,k,t}$ Volume of the product p stored at the RM k in the time period t.

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APPENDIX A

TABLE A1 The average daily demand of RMs

RM	Demand (ton/day)	RM	Demand (ton/day)	RM	Demand (ton/day)	RM	Demand (ton/day)
C1	533.45	C9	439.37	C17	524.58	C25	420.27
C2	252.28	C10	889.55	C18	553.46	C26	124.11
C3	392.91	C11	165.79	C19	327.79	C27	389.04
C4	133.91	C12	413.21	C20	215.86	C28	57.53
C5	460.21	C13	355.45	C21	359.47	C29	240.00
C6	134.14	C14	5.83	C22	349.15	C30	537.26
C7	298.07	C15	425.79	C23	3046.87	C31	98.63
C8	287.07	C16	329.76	C24	806.30		

RMs, Retail markets.

TABLE A2 Average daily production of refineries

Refinery	Production (ton/day)
R1	7 123.28
R2	4 383.56
R3	1 307.94
R4	958.90

TABLE A3 Maximum sending capacity of refineries (ton/day)

Transport mode	R1	R2	R3	R4
Railway	2 684.93	2 191.78	821.92	958.90
Pipeline	5 095.89	1 556.16	547.95	0.00
Road	828.49	1095.89	136.99	950.68
Waterway	0.00	0.00	0.00	0.00

TABLE A4 Maximum sending capacity of SDs (ton/day)

Transport mode	SD1	SD2	SD3	SD4
Railway	1 260.27	2 739.73	4 931.51	0.00
Pipeline	0.00	4 602.74	0.00	0.00
Road	958.90	517.26	2 958.90	821.92
Waterway	0.00	0.00	0.00	1 917.81

SD, Storage depot.

APPENDIX B

TABLE B1 The results of transport plan when there is no satisfaction objective in the model (ton/30 days)

Refineries and Storage Depots	Transport mode	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
R1	Railway	0	0	0	4017.144	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	Railway	0	0	0	0	0	0	0	0	0	26 686.34	0	0	0	0	12 773.54	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	8612.039	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R3	Railway	0	1059.394	0	0	0	3740.606	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4	Railway	9104.157	0	0	0	0	283.6572	0	0	13 181.14	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD1	Railway	0	0	0	0	0	0	0	0	0	0	0	0	10 663.47	174.7821	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD2	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	6899.364	0	0	0	13 806.14	0	0	0	0	0	4973.546	12 396.2	0	0	0	9892.863
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD3	Railway	0	6508.869	11 787.28	0	0	0	8942.212	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continues)

TABLE B1 (Continued)

Refineries and Storage Depots	Transport mode	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31
R1	Railway	0	0	0	6475.726	10 784.19	0	39 571.57	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	Railway	0	15 845.87	0	0	0	0	10 447.67	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	19 333.17	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R3	Railway	0	0	0	0	0	0	0	0	0	0	0	0	7200	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD1	Railway	15 737.45	758.0449	0	0	0	10 474.48	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD2	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	9833.665	0	0	0	22 053.7	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD3	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	16 117.81	2958.904
	Waterway	0	0	0	0	0	0	0	24 189.04	12 608.22	3723.288	11 671.23	1726.027	0	0	0

(Continues)

TABLE B2 The results of transport plan when the unit satisfaction cost is set as 1×10^9 yuan in the model (ton/30 days)

Refineries and Storage Depots	Transport mode	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16
R1	Railway	0	0	0	4017.137	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	Railway	0	0	0	0	0	0	0	0	0	26 686.02	0	0	0	0	12 773.46	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	8612.008	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R3	Railway	0	1059.285	0	0	0	3740.74	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4	Railway	9098.823	0	0	0	0	283.5159	0	0	13 181.06	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD1	Railway	0	0	0	0	0	0	0	0	0	0	0	0	10 663.41	174.7821	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD2	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	6904.606	0	0	0	13 806.06	0	0	0	0	0	4973.535	12 396.14	0	0	0	9892.816
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD3	Railway	0	6508.958	11 787.22	0	0	0	8942.177	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(Continues)

TABLE B2 (Continued)

Refineries and Storage Depots	Transport mode	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30	C31
R1	Railway	0	0	0	6475.704	10 784.12	0	39 571.67	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R2	Railway	0	15 845.48	0	0	0	0	10 448.46	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	19 333.2	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R3	Railway	0	0	0	0	0	0	0	0	0	0	0	0	7199.975	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD1	Railway	15 737.33	758.2897	0	0	0	10 474.4	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD2	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	9833.618	0	0	0	22 049.19	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD3	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Waterway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SD4	Railway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pipeline	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Road	0	0	0	0	0	0	0	0	0	0	0	0	0	16 117.69	2958.9
	Waterway	0	0	0	0	0	0	0	24 188.8	12 608.15	3723.281	11 671.18	1726.026	0	0	0