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Planning of a flexible refined products transportation network in response to emergencies

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ARTICLE INFO

Keywords:
Transportation
Refined products
Flexibility
Oil industry
Disruption

ABSTRACT

The stable supply of refined products is a vital measure to maintain national security and economic development. However, unexpected accidents and incidents, such as pipeline failures, natural hazards, and even this Covid-19 period can disrupt the supply of refined products to the end-users, leading to shortages on the demand side. This issue should be considered in advance in the planning process to increase transportation flexibility. In this paper, a MILP model-based method is proposed to increase the operational flexibility of refined products transportation. This model takes into account several failure conditions of routes during the transportation process and determines the backup transport route plans. The illustration case study demonstrates how to build a more flexible refined products transportation process through expanding transport and sending capacities to satisfy the demand for refined products in market depots. The results show that the capacity expansion plans are different when disruptions are individually and simultaneously considered, a 33.60% difference in the expansion cost. The proposed method could be helpful to ensure the supply of retail markets when facing emergencies.

1. Introduction

The gasoline consumption of China is due to reach 125.1 Mt in 2021 (Xu et al., 2021). A well-running supply chain is required to ensure that such a huge amount of refined products can be transported smoothly from the refineries to the markets.

The primary level of refined products transportation network studied in this paper is part of the refined products supply chain. The transportation network is operated from refineries to market depots. The distribution of refined products is the focus but without the consideration of other supply chain activities such as production, inventory management, and vending (Zhang, 2006). The goal is to meet the needs of the downstream market for different types of refined products. An operable and money-saving distribution plan should be determined to achieve this purpose.

In the distribution plan formulated by the operator of the refined products transportation, various transportation modes should be rationally arranged based on the production of refineries, the inventory of transit depots and market depots. The maximum delivery capacity of each transportation mode and the sending capacity of refineries and transit depots should be considered. The goals include minimising the transportation cost and maximising the satisfaction rate of the market depots.

Guarantee the supply of refined products is the priority of sales and transport companies. However, the end-user market shortage and fears of shortage exist. Such as the coronavirus epidemic, which has severely disrupted the input supply of some supply chains, e.g., the poultry supply chain (Palouj et al., 2021).

There are occasions that the operation of refined products transportation is affected by some unexpected factors, such as the sudden increase in the demand of market depots, the totally or partly shutdown of upstream refineries, the outage of transportation facilities. For example, the offline of the Colonial pipeline in 2021 caused fear of refined products shortage in the US East Coast (Navarro, 2021), the 2008 Wenchuan earthquake, which caused the transport routes of refined products to shutdown (Xinhua News Agency, 2008), and in the COVID-19 pandemic period when the energy supply-demand balance (Jiang et al., 2021) and by a worldwide vaccination campaign (Klemeš.
et al., 2021), as well as the transport and sale schemes, are significantly influenced (Norouzi et al., 2020). Many factors in a transport network of refined products are affecting the satisfaction of the end-user market.

In the daily operation of the supply of the refined products chain, there are always some occasions that unexpected events happen. Some accidents may occur during the operation of the refined products pipeline, such as corrosion (Shafeek et al., 2021), equipment failure (Alves and Lima, 2021), pipeline leakage (Zheng et al., 2021), etc. If the accidents are severe, partial sections or the whole pipeline will be shut down, affecting the normal distribution of refined products, which may result in a shortage in the downstream market.

Refinery accidents such as explosions (Isimite and Rubini, 2016), fire incidents (Shaluf et al., 2003), failure of refinery equipment (Etminanfar et al., 2020), etc., will affect the normal production of the refinery, causing disruptions of equipment or suspension the delivery of the refined product. In addition, other accidents, as, e.g. depot explosions (Xie et al., 2021), would also have a significant impact on the product of the refined oil, resulting in the shortage of the downstream market.

These occasions are barriers for transportation to achieve the main goals of reducing shortage and increasing uptime (Emenike and Falcone, 2020). These two goals are vital as the shortage will affect peoples’ lives the industrial production and even cause economic recessions. Meanwhile, with the intelligent trends in the oil and gas industry (Wang et al., 2019), a quick response becomes possible. It is important to design a flexible transportation network that can handle unusual issues, strengthen the emergency measures when the accident happens, and ensure the efficient and precise configuration of refined products, and reduce transportation costs.

There are some existing contributions focused on the optimisation of refined products transportation network, or on the supply chain, to reduce total cost in strategic, tactical, and operation levels. Lima et al. (2018) developed a stochastic programming model for tactical planning of downstream oil supply chains. The scenario tree approach was applied to tackle uncertainties, including oil price and demand. A real-world case of Portugal was studied. Wang et al. (2019) proposed a MILP model which considers both refined products distribution planning and new pipeline routes planning. The demand uncertainty of the refined products was considered, and a three-level supply chain network was modelled. Zhou et al. (2019) developed a stochastic model for a coal-to-liquid supply chain to determine facility location, coal purchase plan, transport route and amount, and the number of vehicles. Pudasaini (2021) proposed a multi-objective mixed-integer linear programming model for strategic and tactical planning of downstream petroleum supply chain (DPSC). The demand uncertainty was modelled using the scenario trees, and both the transport cost and product loss cost were considered. Lima et al. (2021) considered the uncertainties of network costs and refined products demands in the design and plan of a downstream oil supply chain. A mixed-integer linear programming model was developed, and fuzzy mathematical programming was applied to deal with the uncertainty. A case of the Brazilian oil network was studied with the objective function of the total cost. Wang et al. (2021) studied the fair profit allocation of a refined products supply chain and optimised the transport plan of refined products distributed from refineries to transit depots and customers to get the Nash bargaining solution.

Some studies integrated the environmental cost in the refined products transport and supply chain optimisation. Yuan et al. (2019b) quantified the impacts of pipeline network reform on the downstream oil supply chain of China. A mathematical programming model was developed to determine the transport plan of refined products. The performance of reformulation in five scenarios on energy, economy, and environment was assessed. Wang et al. (2020a) proposed a method for simultaneously considering the economic and environmental costs for refined products supply chain optimisation at the operational level. GHG and SO2 emissions were calculated together, with the total cost was minimised.

The policy can also have an impact on the efficiency of supply chains (Zheng et al., 2020). Studies showed that applying advanced energy-saving technical measures for pipelines (Yuan et al., 2019a) and the interconnectivity of infrastructures of different companies (Yuan et al., 2020b) can help to improve the efficiency of refined products supply chains.

There are a few pieces of the research study the disruptions in the refined products transportations. One aspect is reliability. Wang et al. (2020b) proposed a framework to assess the reliability of refined products supply chains. A MILP model was developed to simulate the operation of the supply chain, and indices were proposed to evaluate the performances under several scenarios. Yuan et al. (2020a) studied two levels, i.e., provincial level and regional level, to evaluate the downstream oil supply security in China. The vulnerability of the oil supply network was studied by calculating the oil shortage amount in scenarios of different levels of oil import disruption, duration times, and initial inventory levels. A downstream oil supply chain planning model was developed for the calculation. Zhou et al. (2020) developed a supply reliability evaluation method for multi-product pipeline systems. The pump failures were considered, the stochastic failure characteristic was described by the discrete-time Markov process, and the system states transition was simulated by the Monte Carlo method.

However, the reliability study aims to locate and analyse the weak points in the supply chain and strengthen these weak points to increase the satisfaction of the market depots. While in the flexibility study, the main aim is to find an alternative plan to compensate for the loss caused by the disruption. The strategic, tactical, and operational decision-making of the supply chain when responses to dramatic disruptions were studied by Kumar and Sharma (2021) recently to help provide guidelines.

The contributions of this work are as follows:

(i) A method is proposed for refined products transportation network optimisation under disruption to tackle unexpected situations and to satisfy the market depots.
(ii) The proposed operating level model for refined products transportation network optimisation integrates the transport and sending capacity expansion.
(iii) This model can be used to predetermine the emergency measures before the disruption happens. The facility sending capacity expansion for some transport modes can be determined as the backup. When the disruption happens, it would be easier to switch to alternative plans as reserved capacities have been determined.
(iv) The expansion plan of individual disruption and the case that simultaneously considers several disruptions in a model are compared.

The rest of this work is as follows. In Section 2, the mathematical model and procedure of how to determine the alternative plans are introduced. In Section 3, a refined products transportation network in a region of China is studied to verify the effects of the proposed method. Section 4 summarises the work and provides the outlook.

2. Model and procedure

The refined products transportation network studied in this paper has three levels of facilities, i.e., refineries, transit depots, and market depots. Refined products are produced in the refineries, transported via transit depots, or directly to the market depots as sinks. There are transport routes between these facilities. The transport mode is related to the existing infrastructure, refined products sending equipment and receiving equipment. The transit depots can receive refined products from upstream refineries, store the refined products, and distribute them to the market depots. Some refineries and transit depots have pipeline connections to reduce the transport cost.
2.1. Modelling assumptions

The following assumptions have been made for model formulation:
(i) The planning of the refined products transportation network is operated by a company, and the refined products can be transported through railway, pipeline, waterway, and road.
(ii) The inventory in market depots is not sufficient to meet the demand of the market depot when disruption occurs.
(iii) The production capacities of refineries and the demand for market depots are fixed.
(iv) The current sending capacity and transport capacity are known, and they can be extended.

2.2. Model development

In the developed model, givens are:
(i) Locations of refineries, transit depots, and market depots.
(ii) Production capacity of refineries and demand of market depots.
(iii) The existing routes between facilities, their distances, and their current maximum transport capacities by four types of transport mode.
(iv) Unit prices of four types of transport mode, and the prices for extending the transport and sending capacities.

It is necessary to estimate:
(i) The distribution plan of the refined products transportation network.
(ii) The routes that should be expanded and the sending capacity that should be increased when disruption of current routes happens.

2.2.1. Objective function

\[ f_{\text{min}} = C^T + CN + C^TN \]  
(1)

The objective function (1) in this model is the sum of transport cost, sending capacity expansion cost, and transportation capacity expansion cost.

2.2.2. Transport cost constraints

\[ C^T = \sum_{i} \sum_{r} \sum_{t} \sum_{s} X_{i,j,r,t,s}^A C_{i,j,r,t,s}^U + \sum_{j} \sum_{k} \sum_{r} \sum_{t} \sum_{s} X_{j,k,r,t,s}^A C_{j,k,r,t,s}^U + \sum_{j} \sum_{k} \sum_{r} \sum_{t} \sum_{s} X_{j,k,r,t,s}^A C_{j,k,r,t,s}^U \]  
(2)

Where \( X_{i,j,r,t,s}^A \) and \( X_{j,k,r,t,s}^A \) are volumes for transporting refined products from 1) refinery \( i \) to transit depot \( j \), 2) from refinery \( i \) to market depot \( k \), and 3) from transit depot \( j \) to market depot \( k \) by transport mode \( r \) at time slice \( t \) in scenario \( s \). \( C_{i,j,r,t,s}^U \), \( C_{j,k,r,t,s}^U \), and \( C_{j,k,r,t,s}^U \) are corresponding unit transport prices. \( L_{i,j,r} \), \( L_{j,k} \), and \( L_{i,j,k} \) are distances for transportation.

The total transport cost is the sum of transport cost of three types of routes, i.e., from refinery to transit depot, from refinery to a market depot, and from transit depot to market depot.

2.2.3. Material balance constraints

\[ V_{L,i,s,t} = V_{L,i-1,s,t} + V_{P} + \sum_{k} \sum_{j} X_{i,k,s_j,t,s}^A - \sum_{j} \sum_{r} X_{j,s_j,t,s}^A \]  
(3)

\[ V_{S,j,s,t} = V_{S,j-1,s,t} + \sum_{j} \sum_{r} X_{j,s_j,s_{j+1},t,s} - \sum_{k} \sum_{r} X_{j,k,s_{j+1},t,s} \]  
(4)

\[ V_{Z,k,s,t} = V_{Z,k-1,s,t} + \sum_{j} \sum_{r} X_{j,s_{j-1},s_{j+1},t,s} - \sum_{j} \sum_{r} X_{j,k,s_{j+1},t,s} - p_{k,s,t} \]  
(5)

Where \( V_{L,i,s,t} \), \( V_{S,j,s,t} \), and \( V_{Z,k,s,t} \) are the volume of refined products storage at refinery depot, transit depot, and market depot at time slice \( t \); \( V_{P} \) is the production volume at time slice \( t \) for refinery \( i \); and \( D_{s,t} \) is the demand of refined products for market depot \( k \) at time slice \( t \) in scenario \( s \).

Constraints (3–5) are material balance constraints for refineries, transit depots, and market depots. For a refinery, the volume of refined products storage at time slice \( t \) equals the volume at time slice \( t-1 \) plus the production and minus the volume transported to the storage and market depots through all transport modes. For a transit depot, its volume at time slice \( t \) equals the volume at the previous time slice plus the amount transported from refineries and minus the amount transported to market depots. While for a market depot, its volume at time slice \( t \) is the sum of the volume at the previous time slice and the volume from refineries and transit depots, then minus the demand.

2.2.4. Capacity constraints

\[ X_{i,j,r,s,t}^\text{min} \leq X_{i,j,r,s,t}^A \leq X_{i,j,r,s,t}^\text{max} \]  
(6)

\[ X_{j,k,r,s,t}^\text{min} \leq X_{j,k,r,s,t}^A \leq X_{j,k,r,s,t}^\text{max} \]  
(7)

\[ X_{j,k,r,s,t}^\text{min} \leq X_{j,k,r,s,t}^A \leq X_{j,k,r,s,t}^\text{max} \]  
(8)

Where \( X_{i,j,r,s,t}^\text{max} \), \( X_{j,k,r,s,t}^\text{max} \), and \( X_{j,k,r,s,t}^\text{max} \) are the maximum transport capacity of the refined products transportation network in scenario \( s \) after the new route expansion. For those transport routes that are disrupted in scenario \( s \), they can be set as 0. \( X_{i,j,r,s}^\text{min} \), \( X_{i,j,r,s}^\text{min} \), and \( X_{i,j,r,s}^\text{min} \) are the minimum transport capacity of the refined products in routes.

Constraints (6–8) ensure that the transport volume of each route is in a feasible transport volume range. Each transport route has its minimum and maximum transport capacities at each time slice. For railway and road, the amount is restricted by the number of tanks or vehicles, while for the pipeline, to ensure safe transport, the amount cannot be lower than the minimum transport restriction and cannot exceed the highest transport capacity.

\[ \sum_{j} X_{i,j,r,s,t}^A + \sum_{k} X_{j,k,r,s,t}^A \leq S_{i,r,s,t}^\text{max} \]  
(9)

\[ \sum_{k} X_{j,k,r,s,t}^A \leq S_{j,r,s,t}^\text{max} \]  
(10)

Where \( S_{i,r,s,t}^\text{max} \) is the maximum sending capacity of refineries \( i \) for transport mode \( r \) in scenario \( s \), and \( S_{j,r,s,t}^\text{max} \) is the maximum sending capacity of transit depot \( j \) for transport mode \( r \) in scenario \( s \).

Constraints (9–10) restrict the sending capacity of refineries and transit depots at each time slice. The number of equipment or facilities for sending refined products through different ways are limited. For example, the number of crane tubes which is used for injecting refined products into the tanker truck is fixed, and the amount of refined products which is sent to road transport has its maximum volume.

2.2.5. Capacity expansion constraints

\[ X_{i,j,r,s,t}^\text{max} \leq X_{i,j,r,s,t}^N + X_{i,j,r,s}^\text{CM} \]  
(11)

\[ X_{i,j,r,s,t}^N = \sum_{g} (B_{i,j,g}^R \times P_{g}^E) \]  
(12)
\[ \sum_{g} B_{i,k,r,g}^{E} \leq 1 \] (13)

Where \( X^{N}_{j,r} \) is the expanded capacity for the transport route from refinery \( i \) to transit depot \( j \) by transport mode \( r \) of the current refined products transportation network, which is a decision variable in the model; \( B_{i,k,r,g}^{E} \) is a binary variable that represents the expansion level of the transport mode.

For the transport route from refinery to transit depot, constraint (11) ensures that the maximum transport capacity of route \( i \) to \( j \) by transport mode \( r \) in scenario \( s \) should be lower than the previous capacity plus the expanded capacity. The maximum transport capacity equals the current transport capacity plus the new or expanded transport capacity. One of the main objectives of this study is to determine how much capacity should be expanded or newly developed to ensure the flexible operation of the transportation network under unusual conditions. Constraint (12) calculates the expanded capacity of route \( i \) to \( j \) by transport mode \( r \). Constraint (13) ensures that at most 1 level transport expansion should be selected.

\[ X^{\text{Max}}_{i,k,r} \leq X^{N}_{i,k,r} + X^{\text{CMax}}_{i,k,r} \] (14)

\[ X^{N}_{i,k,r} = \sum_{g} B_{i,k,r,g}^{E} \times P_{g}^{E} \] (15)

\[ \sum_{g} B_{i,k,r,g}^{E} \leq 1 \] (16)

For other routes, such as from refineries to market depots and from transit depots to market depots, similar constraints can be formulated. Constraints (14–16) are formulated for the routes from refineries to market depots.

\[ X^{\text{Max}}_{i,j,k} \leq X^{N}_{i,j,k} + X^{\text{CMax}}_{i,j,k} \] (17)

\[ X^{N}_{i,j,k} = \sum_{g} B_{i,j,k,g}^{E} \times P_{g}^{E} \] (18)

\[ \sum_{g} B_{i,j,k,g}^{E} \leq 1 \] (19)

Constraints (17–19) are used for the routes from transit depots to market depots.

\[ S^{\text{Max}}_{i,j,r,s} \leq S^{N}_{i,j,r} + S^{\text{CMax}}_{i,j,r,s} \] (20)

\[ S^{N}_{i,j,r} = \sum_{h} B_{i,j,r,h}^{S} \times P_{h}^{S} \] (21)

\[ \sum_{h} B_{i,j,r,h}^{S} \leq 1 \] (22)

Where \( B_{i,j,r,h}^{S} \) is a binary variable that represents the expansion level of the sending capacity of facilities.

For refineries, Constraint (20) ensures that the maximum sending capacity of the refinery \( i \) for transport mode \( r \) in scenario \( s \) should be lower than the previous sending capacity plus the expanded sending capacity. Constraint (21) calculates the expanded capacity of refinery \( i \) for transport mode \( r \). Constraint (22) ensures that at most 1 level of facility expansion should be selected.

\[ S^{\text{Max}}_{i,r,s} \leq S^{N}_{i,r} + S^{\text{CMax}}_{i,r,s} \] (23)

\[ S^{N}_{i,r} = \sum_{h} B_{i,r,h}^{S} \times P_{h}^{S} \] (24)

\[ \sum_{h} B_{i,r,h}^{S} \leq 1 \] (25)

For transit depot, similar constraints as Constraints (23–25) can be formulated to determine the expansion capacity.

2.2.6. Expansion cost constraints

\[ C^{\text{SN}} = \sum_{i} \sum_{r} \sum_{h} B_{i,r,h}^{S} C_{r,h}^{S} \] (26)

\[ C^{\text{TN}} = \sum_{i} \sum_{r} \sum_{g} B_{i,k,r,g}^{E} C_{r,g}^{E} + \sum_{i} \sum_{r} \sum_{h} B_{i,j,r,h}^{S} C_{r,h}^{S} \] (27)

Where \( C_{r,h}^{S} \) and \( C_{r,g}^{E} \) are costs for expanding sending and transport capacities for transport mode \( r \) and in their levels, which are indexed by \( h \) and \( g \).

Eq. (26) calculates the sending capacity expansion cost of facilities, including refineries and transit depots, and Eq. (27) calculates the transport capacity expansion cost of every type of transport route.

2.3. Scenarios

There are several types of route disruptions in the supply of the refined products chain, including railway route failure, pipeline failure, waterway route failure, and road route failure. These routes all have the possibility to be disrupted by natural disasters or human errors. When these disruptions happen, it is important to introduce new routes or substitute routes to revive the operation of the refined products transportation network. The basic model in the normal condition plus the constraints of route disruption should be solved to propose the alternative plan. The method can also be used to determine an alternative distribution plan when several disruptions have happened. The scenarios in the next section Case study are based on these route disruption types.

3. Case study

A case is studied to test the proposed method in this section. There are three refineries, two transit depots, and 30 market depots in the studied region. They are distributed as shown in Fig. 1. The case was solved by Gurobi (Gurobi Optimization LLC, 2021), and the optimality gap was set to 0.

Transit depot 1 is affiliated with refinery 2, and a pipeline connects these two stations. Another pipeline starts at refinery 1, connecting market depot numbered 1, 4, 5, 11, 12, 16, 19, 23, 30, and transit depot 2. Transit depot 2 can transport refined oil by a waterway, and market depot numbered 24, 25, 26, 27, and 28 have the unloading capacity of the waterway. The transportation costs for the railway, pipeline, waterway, and road are set as: 0.31 CNY/(km·t), 0.143 CNY/(km·t), 0.1 CNY/(km·t), and 0.68 CNY/(km·t).

First, the original distribution plan without transport disruption is optimised. The results are shown in Fig. 2. Refinery 1 transports refined products to several market depots through pipelines, also to the transit depot 2. Then it further distributes refined products via waterway to these market depots, which can receive from docks. Refinery 2 and transit depot 1 are mainly used to distribute refined products in the southwest part of the studied region. The upper part is distributed by
the railway from the refinery, and the lower part is distributed by the transit depot 1, which receives refined products through the pipeline links these two stations first. The northeast part of the region receives refined products from refinery 3 mainly through railways.

Then several scenarios for transport routes disruption are set as the following:

(i) The railway transport route from refinery 2 to market depot 9 is disrupted.
(ii) Market depot 22 and 29 cannot receive refined products through the pipeline.
(iii) The waterway transport route from transit depot to market depot 23 is disrupted.
(iv) Consider the above three scenarios simultaneously.

In scenario (i), two new transport routes are used to satisfy the demand of market depot 9, the first is a roadway from transit depot 1 to market depot 9, and the second is a roadway from transit depot 2 to market depot 9. The new distribution plan for this scenario is shown in Fig. 3. The influence on the transport cost is minor, only 0.01%.

In scenario (ii), these two market depots need a relatively large volume of refined products, and mainly through pipeline transportation when the whole system operates well. When the pipeline that transports refined products to these two market depots is disrupted, some changes happen to continually satisfy the demand. Refinery 1 starts to transport refined products through railways directly. However, the amount still cannot meet all their requirement. The refined products received from refinery 2 via railway to market depot 22 is increased to make up for the loss brought by the pipeline disruption, which also influences the way that other market depots receive the refined products. The market depot 9 changes its source from refinery 2 to refinery 3, and market depots 14 and 17 change their sources from transit depot 1 to refinery 3, still by railway transport. Market depot 29 receives the refined products from both refineries 1 and 3 through railways. The scheme is shown in Fig. 4.
In this way, the transport cost increases by 2.29%. The change of sources is due to the production capacities of refineries. To compensate for the loss of those two market depots influenced by the pipeline disruption, other refineries and transit depots also have to adjust their distribution plans to ensure the demand of the whole system can be satisfied.

In scenario (iii), the disruption of the waterway stops the market depot from receiving refined products from transit depot 2. As shown in Fig. 5, alternative ways from refinery 3 by road and from transit depot 2 by road should be used to meet the requirement of the influenced market depot, which increases the transport cost by 3.03%. Because of the insufficient sending capacity of refinery 3 and transit depot 2, the cost also happens on the expansion of the sending capacities. In both stations, the road sending mode is selected, which means the current sending capacities of these two stations are limited and should be expanded to better tackle future disruptions.

In scenario (iv), when all three scenarios are considered, the plans for expanding transport and sending capacities are different from the previous individual considerations. The road sending capacity for refinery 3 is extended to satisfy the demand from market depot 8, 9, 22, and 29. The road sending capacity for refinery 1 is also extended to satisfy the requirement from market depots 10, 22, and 29. Unlike the case in scenario (ii), that railway is mainly used, as it requires a little cost to expand the sending capacity. While in scenario (iv), it tends to use more road transport due to the relatively low cost of increasing the road sending capacities of refineries and transit depots. Although the transport cost increases 22.01% compared to the normal condition, the expansion cost reduces 33.6% compared to the sum of the expansion costs of scenarios (i) to (iii). This is because some expansion of routes can be together used for several scenarios. When only one scenario is considered, the model gives the best result only for that scenario, but when several scenarios are simultaneously considered, the model can comprehensively consider these scenarios together and try to maximise the usage of expanded route transport capacities and sending capacities. In this way, the total expansion cost can be reduced. The increase of transport cost is because although some transport modes such as road transport are relatively expensive compared to other routes, it can save capacity expansion cost, which in total, reduces the overall cost. This suggests that to increase the flexibility of the refined products transportation network, it is a good option to expand the sending capacities of depots for road transport as it can adapt to more unexpected situations.

4. Conclusions

This paper optimises refined products transportation network under unexpected disruptions to determine the distribution plan, transport capacity expanding plan, and sending capacity expanding plan. The transportation cost and capacity expansion cost are set as the objective functions. The results show that considering disruptions individually and simultaneously would lead to different expanding plans. In the simultaneous consideration scenario, it tends to expand the sending capacity of refineries and transit depots on the road transportation as it is easy to operate and costs less for increasing the sending capacity. As a result, the simultaneous consideration would reduce the total cost for expansion compared to the sum of the expansion cost individually considered; in this case, it achieves a 33.60% reduction.

The future work should consider the expansion cost in detail – e.g., setting parameters for each route and each facility. In terms of methodological development, the current model could be extended to a stochastic programming model to consider the uncertainties such as demand and production in the distribution and expansion planning.

Nomenclature

Sets and Indices

- $I$: Set of refineries, denoted by index $i$
- $J$: Set of transit depots, denoted by index $j$
- $K$: Set of market depots, denoted by index $k$
- $R$: Set of transport modes, denoted by index $r$
- $T$: Set of time slices, denoted by index $t$
- $S$: Set of scenarios, denoted by index $s$
- $G$: Set of expanding capacities of transport, denoted by index $g$
- $H$: Set of expanding capacities of sending, denoted by index $h$

Continuous Variables

- $C^T$: Transportation cost, CNY
- $C^{SN}$: Sending capacity expansion cost, CNY
- $C^{TN}$: Transportation capacity expansion cost, CNY
- $V_{i,t,s}$: Volume of the product stored at refinery $i$ in the time period $t$ in scenario $s$
- $V_{j,t,s}$: Volume of the product stored at the transit depot $j$ in the time period $t$ in scenario $s$
- $V_{k,t,s}$: Volume of the product stored at the market depot $k$ in the time period $t$ in scenario $s$
- $X_{i,t,s}$: Volume of product transported from the refinery $i$ to the market depot $k$ through transport mode $r$ at time slice $t$ in scenario $s$
- $X_{j,t,s}$: Volume of product transported from the transit depot $j$ to the market depot $k$ through transport mode $r$ at time slice $t$ in scenario $s$
- $S_{i,r,t,s}$: Expanded sending capacity for the refinery $i$ by transport mode $r$ in scenario $s$
- $S_{j,r,t,s}$: Expanded sending capacity for the transit depot $j$ by transport mode $r$ in scenario $s$
- $X_{i,t,s}$: Expanded capacity for the transport route from refinery $i$ to transport depot $j$ by transport mode $r$ in scenario $s$
- $X_{j,t,s}$: Expanded capacity for the transport route from transit depot $j$ to market depot $k$ by transport mode $r$ in scenario $s$
- $X_{i,t,s}$: Maximum transport capacity of the refined products from refinery $i$ to transit depot $j$ by transport mode $r$ in scenario $s$ after new route development and expansion, $t$

Fig. 5. Distribution plan of the refined products transportation network under scenario (iii).
Maximum transport capacity of the refined products from refinery i to market depot k by transport mode r in scenario s after new route development and expansion, t

Maximum transport capacity of the refined products from transit depot j to the market depot k by transport mode r in scenario s after new route development and expansion, t

Maximum sending capacity of refineries i for transport mode r in scenario s, t

Maximum sending capacity of transit depot k for transport mode r in scenario s, t

Binary variables

| Variable | Description |
|----------|-------------|
| $B_E^{i,k,r}$ | Binary variable which represents the expansion level g of the transport mode r from refinery i to transit depot j |
| $B_E^{i,k,r}$ | Binary variable which represents the expansion level g of the transport mode r from refinery i to market depot k |
| $B_E^{i,k,r}$ | Binary variable which represents the expansion level g of the transport mode r from transit depot j to market depot k |
| $B_S^{i,r,h}$ | Binary variable which represents the expansion level h of the sending capacity of refinery i |
| $B_S^{i,r,h}$ | Binary variable which represents the expansion level h of the sending capacity of transit depot j |

Parameters

- $L_{i,j}$ Distance from the refinery i to the transit depot j, km
- $L_{i,k}$ Distance from the refinery i to the market depot k, km
- $C_{U}^{i,k}$ Unit transport price for transporting refined products from refinery i to transit depot j through transport mode r, CNY/(km·t)
- $V_{P}^{i,j,s,t}$ Production volume at time slice t for refinery i, t
- $V_{I}^{i,j,s,t}$ Initial storage volume for refinery i at scenario s, t
- $V_{S}^{j,s,t}$ Initial storage volume for transit depot j at scenario s, t
- $V_{D}^{j,s,t}$ Initial storage volume for market depot k at scenario s, t
- $D_{X}^{i,j,s,t}$ Demand of refined products for market depot k at time slice t in scenario s, t
- $X_{A min}^{i,j,s,t}$ Minimum transport capacity of the refined products from refinery i to transit depot j by transport mode r, t
- $X_{A max}^{i,k,r}$ Minimum transport capacity of the refined products from refinery i to market depot k by transport mode r, t
- $X_{C max}^{i,j,s,t}$ Previous maximum transport capacity from refinery i to transit depot j by transport mode r before expansion, t
- $X_{C max}^{i,k,r}$ Previous maximum transport capacity from refinery i to market depot k by transport mode r before expansion, t
- $X_{C max}^{i,k,r}$ Previous maximum transport capacity from transit depot j to market depot k by transport mode r before expansion, t
- $X_{C max}^{i,k,r}$ The expanded transport capacity for level g, t
- $S_{C max}^{i,r,h}$ Previous maximum sending capacity of refinery i by transport mode r before expansion, t
- $S_{C max}^{i,r,h}$ Previous maximum sending capacity of transit depot j by transport mode r before expansion, t
- $P_{S}^{i,j,s,t}$ The expanded sending capacity for level h, t
- $C_{E}^{i,j,s,t}$ Cost for expanding sending capacity for transport mode r in h level, CNY
- $C_{E}^{i,j,s,t}$ Cost for expanding transport capacity for transport mode r in g level, CNY

**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.

**Acknowledgements**

EU project “Sustainable Process Integration Laboratory – SPIL”, project No. CZ.02.1.01/0.0/0.0/15_003/0000456 funded by EU “CZ Operational Programme Research, Development and Education”, Priority 1: Strengthening capacity for quality research.

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