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A review of multiproduct pipeline scheduling: from bibliometric analysis to research framework and future research directions

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ABSTRACT

Multiproduct pipelines play an important role in ensuring the downstream energy supply as they transport about 70% of refined products. To guarantee the safe and stable operation of pipelines during the scheduling horizon, it is necessary to make a reasonable schedule. During the past two decades, the multiproduct pipeline scheduling problem has been widely studied in the world. In this paper, the bibliometric analysis method is adopted to conduct quantitative analysis and visual research on related literature. Then, through the review of the existing articles, the research framework of multiproduct pipeline scheduling problem is constructed. Finally, the research defects and trends are analyzed. The aim of the paper is to provide a comprehensive understanding of multiproduct pipeline scheduling as well as some directions and inspiration for the future research.

1. Introduction

Refined products account for the majority of energy consumption worldwide. Crude oil is transformed into different types of refined products in refineries, and then conveyed to wharfs and depots through ships, pipelines, trains or trucks (MirHassani and Ghorbanalizadeh, 2008; Qiu et al., 2019; Wang et al., 2019). Among the multiple transportation modes, pipeline is the most efficient mode for transporting large amounts of refined products over long distance, due to its advantages of lower operation costs, higher reliability, less environmental pollution, and less susceptibility to adverse weather (Liao et al., 2018; Cafaro and Cerdá, 2004).

Multiproduct pipelines are the bridges connecting the upstream refineries with the downstream markets, along which there are input stations, receiving depots, dual-purpose depots, pump stations and so on. According to the principle of batches transportation, pipelines usually transport several products in sequence to respective depots (Zhou et al., 2020; Zhou et al., 2019). During the operation and management of multiproduct pipelines, the formulation of pipeline schedule is the key, and the rationality of the schedule will directly affect the operation safety of pipelines and the supply of downstream markets. In the production site, the schedulers mainly adopt the manual method to make a schedule, which requires the schedulers to have high professional level and rich work experience. During the process of schedule formation, unreasonable batch sequence and injection volume will lead to the increase of contamination produced by the adjacent products transported in the pipeline, which is a severe accident for actual production. Meanwhile, the deviation of delivery time and volume may cause the increase of inventory cost or shortage of products at depots. With the development of multiproduct pipelines, the topology becomes more complex, the number of transported batches is increasing, and the operation technology becomes more flexible, which make the pipeline scheduling tends to be more difficult. How to develop a reasonable schedule to satisfy the market demand while ensuring safety and economy of pipeline operation has always been an issue of great focus to people.

Currently, although there are a lot of research articles in this field, few review articles are presented. The existing review articles mainly focused on mathematical modeling and algorithms used for multiproduct pipeline scheduling (Liang et al., 2015; Chen et al., 2020). A few of them also reviewed scheduling models on mathematical aspects, such as objective functions, decision variables and constraints (Chen et al., 2019). There is no comprehensive review from the perspective of development and research framework for pipeline scheduling problem. In this paper, the bibliometric analysis method is used to conduct quantitative analysis and visual research on literature in the field of multiproduct pipeline scheduling. Then, we sort out related research disciplines and construct the research framework in this field. Finally, the research defects and trends are analyzed. This paper aims to review the related work of multiproduct pipeline scheduling in the past two decades, and provide some directions for the future research.

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The rest of the paper is organized as follows. In Section 2, the overview of multiproduct pipeline scheduling is described based on bibliometric analysis. Section 3 summarizes the research framework of multiproduct pipeline scheduling. In Section 4, the existing drawbacks of the current research are discussed, and the feasible future directions are proposed. Finally, the conclusions are provided in Section 5.

2. Overview of the research on the multiproduct pipeline scheduling

2.1. General situation

The advancement of the research on scheduling of multiproduct pipelines is closely related to the development of pipelines. According to the conclusions in Yan et al. (2017), the total length of pipelines in the world will continue to increase year by year. At present, in terms of the mileage of pipelines in the world, the top three countries are the United States, Russia and China, with total mileage reaching 660,000 km, 248,700 km and 131,400 km respectively (Zhu et al., 2019). Fig. 1 presents the evolution of refined product pipelines in China over the last 20 years. As can be seen from the figure, the mileage of pipelines in China is increasing every year, making a great contribution to the development of global pipelines. Then, we select Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) as the data sources, and count the number of the articles related to multiproduct pipeline scheduling in the above two databases. As shown in Fig. 2, the number of articles shows an overall upward trend, which is the same as the development of pipelines worldwide. Over these years, the world's energy demand has slowed down, and many countries have begun to develop renewable energy, which makes the proportion of renewable energy in the world energy consumption gradually increase. However, according to the forecast of International Energy Agency (IEA), oil and gas will still play a dominant role in energy consumption in the future (Kober et al., 2020). It can be inferred that the reasonable schedule of oil resource is still the focus of pipeline operators.

Then, we count the types of articles in the field of multiproduct pipeline scheduling and journals they have been published in, as shown in Fig. 3. For each area in the figure, the number above represents the number of published articles, and the number below represents the proportion. As can be seen from Fig. 3(a), in the past two decades, the total number of articles published in this field is 238, among which the number of research articles is the largest, accounting for 72%, while the number of review articles is the least, accounting for 3%. Meanwhile, we further count the journals in which research articles and review articles published. Table 1 presents the top 9 journals that are ranked by the number of articles. It can be seen that the articles on multiproduct pipeline scheduling are mainly published in the journals of petroleum,

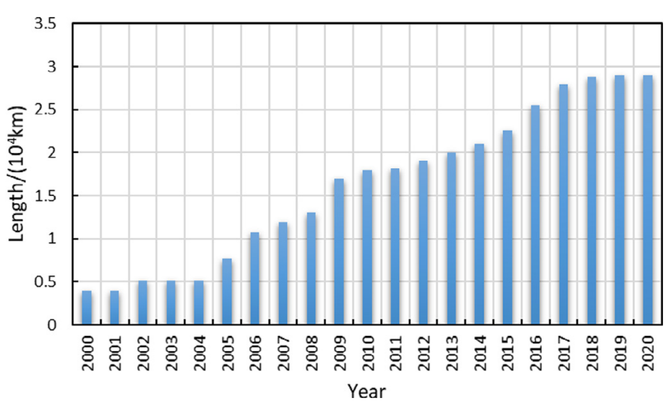

Fig. 1. The evolution of refined product pipelines in China.

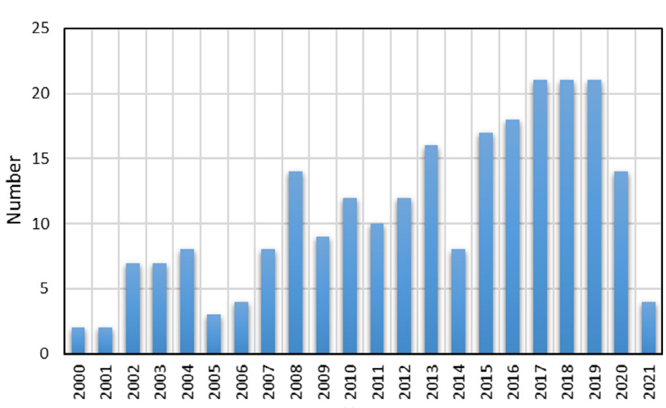

Fig. 2. The number of articles related to multiproduct pipeline scheduling published from 2000 to 2021.

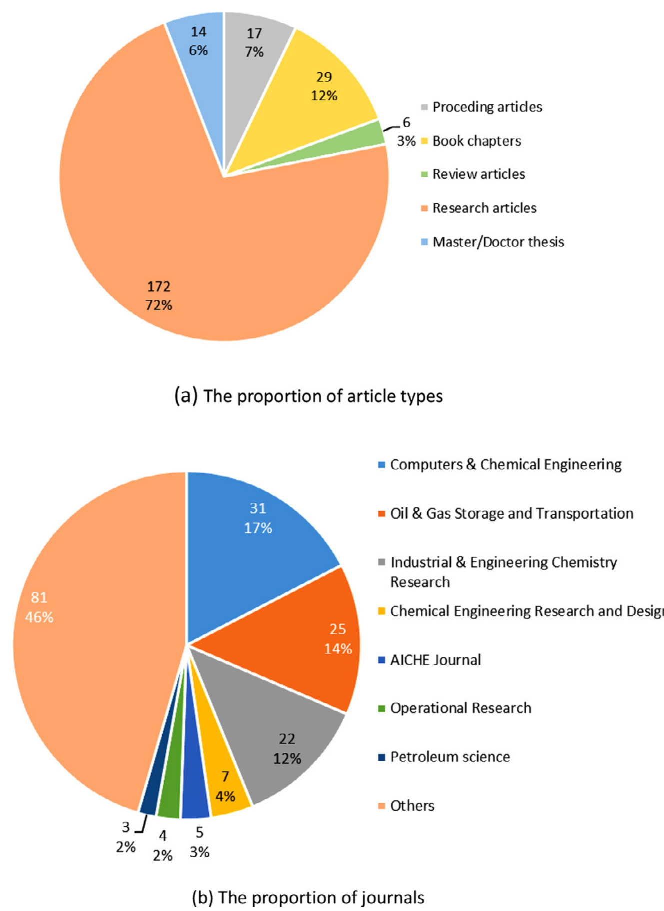

Fig. 3. The proportion of article types and journals.

Table 1
The information of journals.

Rank	Journal	Frequency
1	Computers & Chemical Engineering	31
2	Oil & Gas Storage and Transportation	25
3	Industrial & Engineering Chemistry Research	22
4	Chemical Engineering Research and Design	7
5	AICHE Journal	5
6	Operational Research	4
7	Petroleum Science	3
8	Brazilian Journal of Chemical Engineering	3
9	European Journal of Operational Research	3

chemical engineering and operational research, among which “Computers & Chemical Engineering”, “Oil & Gas Storage and Transportation” and “Industrial & Engineering Chemistry Research” contain the largest number of articles in this field, accounting for 17%, 14% and 12% respectively.

Finally, we make statistics on the research groups who have always studied pipeline scheduling problem in the world, as shown in Table 2. It can be seen that the countries studying this issue mainly include Argentina, Brazil, China, Finland, Iran, Portugal, Spain and USA. Most researchers mainly focus on the short-term scheduling of small-scale pipeline systems, and some of them also extend their research to the lone-term scheduling of small-scale pipeline systems or short-term scheduling of large-scale pipeline systems.

2.2. Co-occurrence analysis of discipline

Through the analysis of the articles, it can be found that the research on multiproduct pipeline scheduling is an interdisciplinary and comprehensive issue, involving multiple disciplines. To further analyze the discipline structure of this field, we use bibliometric analysis method to construct the co-occurrence network of disciplines based on the collected literature. Fig. 4 shows the co-occurrence network of subject categories. In the figure, each node represents the discipline and its size reflects the corresponding occurrence frequency. The several rings whose color of the outer ring is purple denote the subjects with high centrality (Chen et al., 2012). The links between the nodes represent that the studied problem involves multiple disciplines. By visualizing the interconnections among disciplines, it can be seen that the research on multiproduct pipeline scheduling covers a wide range of subjects, with ENGINEERING as the core discipline, followed by CHEMICAL ENGINEERING, COMPUTER SCIENCE and so on.

In the co-occurrence network, different clusters are connected by key nodes with high centrality and citation frequency. The higher node centrality is, the stronger its influence in the network (Chen et al., 2012). Table 3 lists the top five subjects, including their categories, frequency and centrality. From the table, it can be seen that the centrality of ENGINEERING is bigger than other disciplines, then followed by OPERATIONS RESEARCH & MANAGEMENT SCIENCE and COMPUTER SCIENCE. Therefore, it can be concluded that ENGINEERING, OPERATIONS RESEARCH & MANAGEMENT SCIENCE and COMPUTER SCIENCE are the three most important disciplines in the research on multiproduct

Table 2
The information of research groups in the world.

Country	Affiliation	The latest achievements					
		The topology of pipelines	The number of nodes	The number of lines	Scheduling horizon/d	Solving time/s	Ref
Argentina	Instituto de Desarrollo Tecnológico para la Industria Química	Straight pipeline system with multiple-sources	4	1	10	687.5	Cafaro et al. (2015)
Brazil	Universidade Tecnológica Federal do Paraná	Straight pipeline system with single source and multiple terminals	6	1	30	1,476.2	Meira et al. (2020)
		Straight pipeline system with multiple-sources	6	1	30	926.3	Meira et al. (2021)
	University of São Paulo	Straight pipeline system with single source and multiple terminals	6	1	5.4	4,040.8	Rejowski and Pinto (2008)
	Universidade Federal de Uberlândia	Straight pipeline system with single source and distribution center	2	1	5	2,655.8	Dimas et al. (2018)
China	China University of Petroleum-Beijing	Straight pipeline system with single source and multiple terminals	5	1	15	185.6	Xu et al. (2021)
		Straight pipeline system with multiple-sources	5	1	5	506	Liao et al. (2019a)
		Tree-Structure pipeline network	9	3	12.5	1,345	Liao et al. (2019b)
		Mesh-Structure pipeline network	8	6	6.6	2,147	Liao et al. (2019c)
		Straight pipeline system with single source and multiple terminals	6	1	12	1,272	Chen et al. (2017)
		Tree-Structure pipeline network	4	3	5.7	129	Chen et al. (2019)
		Mesh-Structure pipeline network	4	3	4.4	13.6	Chen et al. (2019)
Finland	Aalto University	Straight pipeline system with single source and multiple terminals	4	1	8.3	2,480	Mostafaei et al. (2021a)
		Straight pipeline system with multiple-sources	6	1	8.1	4,602	Mostafaei et al. (2021b)
Iran	Amirkabir University of Technology	Straight pipeline system with single source and multiple terminals	4	1	10	325	Moradi et al. (2019)
	Islamic Azad University	Tree-Structure pipeline network	6	3	5.4	2,196	Taherkhani (2020)
Portugal	Universidade de Lisboa	Straight pipeline system with single source and multiple terminals	Cooperate with Aalto University (Mostafaei et al., 2021a)				
		Straight pipeline system with multiple-sources	Cooperate with Aalto University (Mostafaei et al., 2021b)				
		Tree-Structure pipeline network	Cooperate with China University of Petroleum-Beijing (Liao et al., 2019b)				
		Mesh-Structure pipeline network	Cooperate with China University of Petroleum-Beijing (Liao et al., 2019c)				
		Straight pipeline system with multiple-sources	Cooperate with Universidade Tecnológica Federal do Paraná (Meira et al., 2020)				
		Straight pipeline system with single source and multiple terminals	Cooperate with Universidade Tecnológica Federal do Paraná (Meira et al., 2021)				
Spain	Complutense University	Mesh-Structure pipeline network	6	7	6.3	18,000	Herrán et al., (2012)
USA	Lamar University	Straight pipeline system with single source and multiple terminals	5	1	9.2	790	Yu et al., (2020)

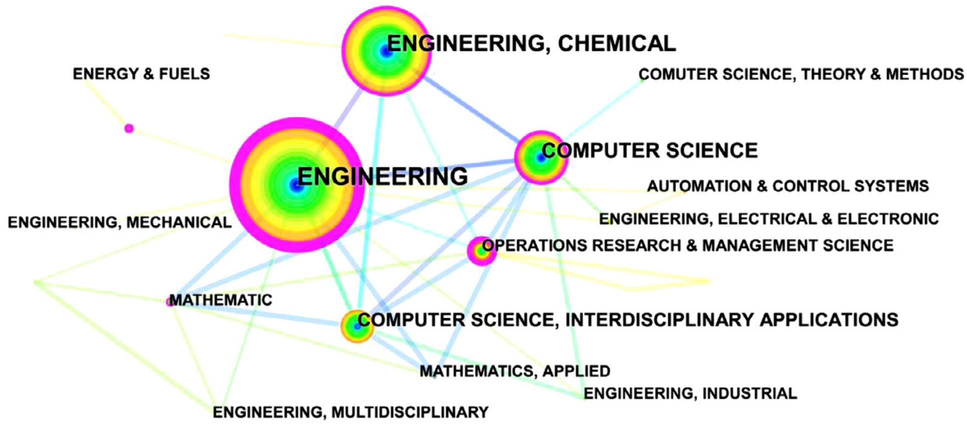

Fig. 4. Co-occurrence network of subjects.

Table 3
The index information of subjects.

Rank	Subject	Frequency	Centrality
1	ENGINEERING	111	1.08
2	CHEMICAL ENGINEERING	85	0.22
3	COMPUTER SCIENCE	52	0.34
4	COMPUTER SCIENCE, INTERDISCIPLINARY APPLICATIONS	39	0.06
5	OPERATIONS RESEARCH & MANAGEMENT SCIENCE	22	0.42

pipeline scheduling. As the center of interdisciplinary networks, these disciplines act as the bridges connecting the entire network.

3. Research framework

Section 2 introduces the overview of the research on the multiproduct pipeline scheduling in terms of the number of published articles, the types of articles and published journals, research groups in the world. To explore the research focuses of this field, this section further analyzes the literature collected in the previous section and summarizes the research framework, as shown in Fig. 5. Firstly, it is necessary to determine the scheduling modes of pipelines. If the selected mode is different, the model structure and decision variables involved in scheduling models are also different. After the mode is selected, the research objects need to be determined, such as the topology of pipelines, the operation constraints and the accuracy of schedule. Then, the suitable modeling methods need to be selected to establish a scheduling model. Finally, a suitable solution strategy should be selected based on the model structure. In this section, the research status of each link will be reviewed.

3.1. Scheduling modes of pipelines

Under different scheduling modes, the developed scheduling models and their decision variables and parameters' properties are also different. Before studying the scheduling of a pipeline, it is necessary to determine its scheduling mode. The scheduling modes of pipelines can be divided into deterministic scheduling and scheduling under uncertain environment, and each mode can be further divided in detail.

3.1.1. Deterministic scheduling

Deterministic scheduling refers that the schedule within a certain period is determined in advance when the parameters are all deterministic, so that the pipeline operation can reach an optimal target. It can be divided into static scheduling and dynamic scheduling according to whether adjustment is required during the execution of schedule.

Static scheduling. Static scheduling aims to prepare a schedule in advance according to market demand within the scheduling horizon and pipeline transportation capacity, without considering the adjustment of the schedule during its implementation. Aiming at different operation modes, the static scheduling model of multiproduct pipelines can be divided into supply-based scheduling model (Zhang et al., 2016; Liao et al., 2018) and demand-oriented scheduling model (Cafaro et al., 2015; Liao et al., 2019c; Castro and Mostafaei, 2019).

The input and output of supply-based scheduling model are shown in the orange box of Fig. 6. In the research of supply-based scheduling, the batch arrival time, the starting time of depot operation and the time of flow variation are chosen as the events to divide the time intervals. Then, the scheduling model can be established to determine the delivery schedules of depots, with the initial products in pipeline, the injection schedule of input station, the demand of depots for each batch and the operation constraints are known (Zhang et al., 2016; Zhang et al., 2017). The difficulty of this research is to determine the sequence of time nodes. Furthermore, because the operation mode of multiproduct pipeline is mostly market-oriented, there are few studies on supply-based scheduling.

In the research of demand-oriented scheduling, the initial products in pipeline, the demand volume and time of depots for products, the operation constraints are parameters. The scheduling model is established to determine the delivery schedules of depots and injection schedule of input station. The delivery schedule includes the operation flowrate and time intervals, while injection schedule involves batch sequence, batch size, the injection flowrate and time intervals (Cafaro et al., 2011; Cafaro et al., 2012). The input and output of this model are shown in the green box of Fig. 6. As can be seen from the figure, compared with supply-based scheduling model, demand-oriented scheduling model has more decision variables. The main difference between the two models is that the injection schedule of input station in supply-based scheduling model is the known parameter, while it is the decision variable in demand-oriented scheduling model. For this issue, in addition to the difficulty in determining the sequence of time nodes, the batch sequence of input station injected into pipeline is also difficult to determine.

Dynamic scheduling. However, there are strong uncertainties in multiproduct pipeline system. The variation of market demand and pipeline status may make the schedule obtained through the static scheduling model no longer feasible. Dynamic scheduling models aim to adjust the more operable schedule according to the actual situation, and have gradually become a hot spot in the field of pipeline scheduling. Most of the existing dynamic scheduling models are based on static scheduling models, and they can be divided into reactive scheduling model (Relvas et al., 2007) and rolling scheduling model (Cafaro and Cerdá, 2008).

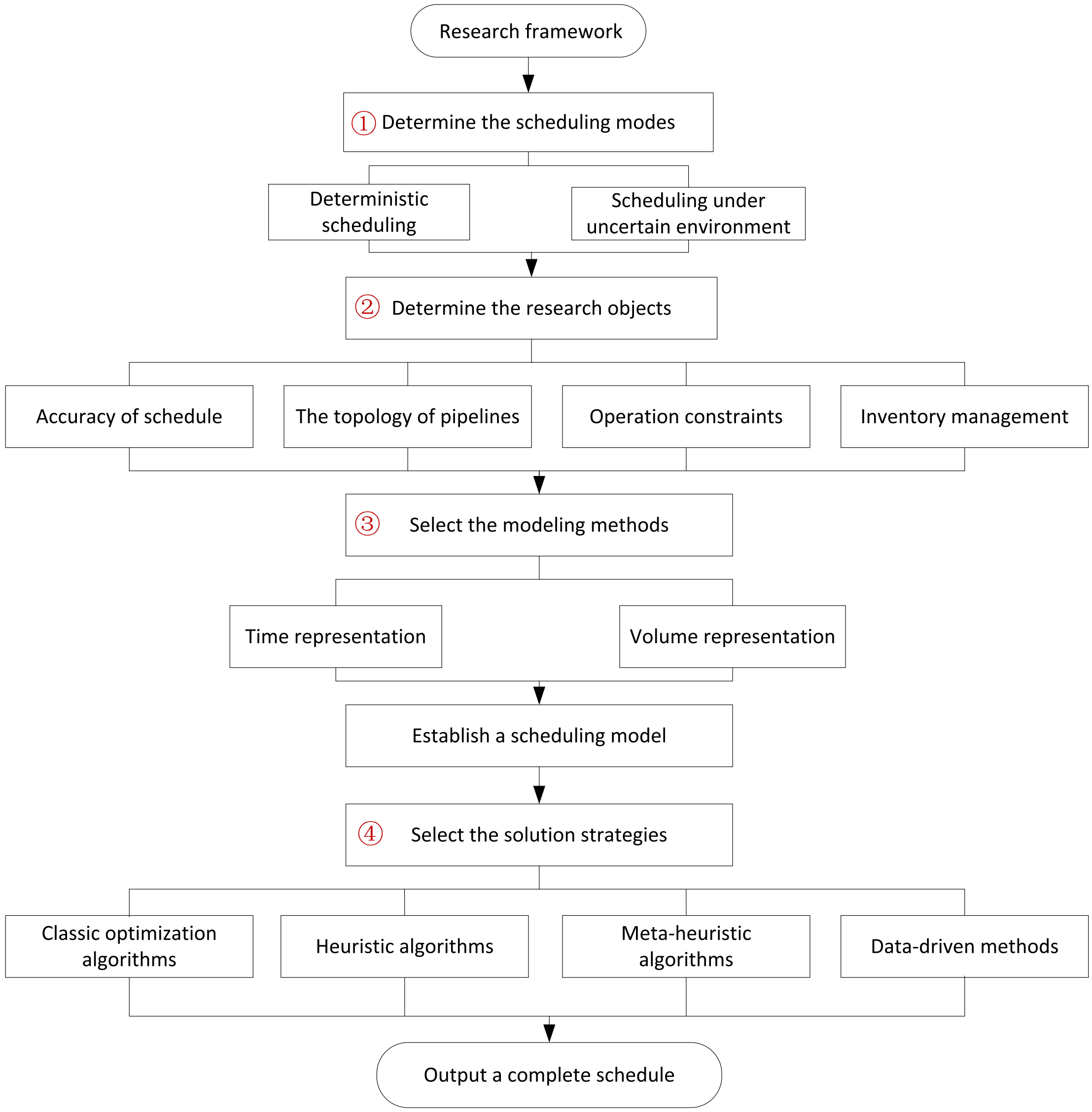

Fig. 5. Research framework of multiproduct pipeline scheduling.

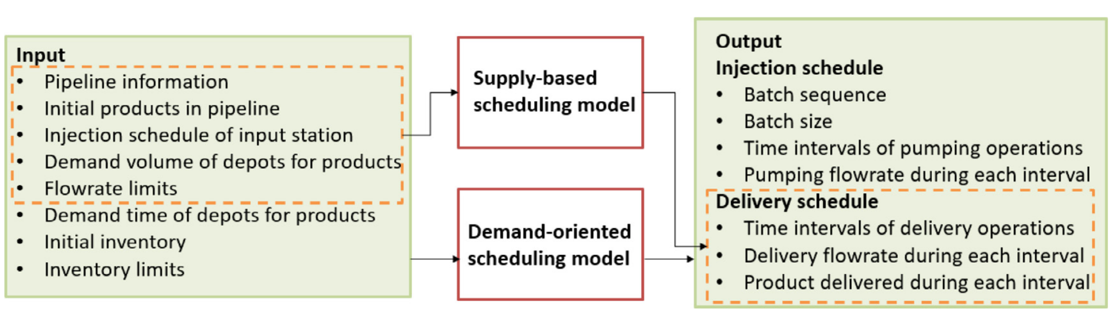

Fig. 6. Input and output of the two models.

In the former research, uncertain events are formulated by mathematical expressions and introduced into static scheduling models as constraints. Relvas et al. (2007) took demand variation, imposition on product sequence, pipeline stoppage, batch volume modification, flowrate adjustment and variation on maximum capacity storage into consideration when modeling, and realized the adjustment of the schedule. For the latter, rolling scheduling is to use the sequential decision-making method to dynamically generate the optimal schedule within the rolling horizon, through forecasting the trend of supply and demand fluctuation based on historical data (Li and Ierapetritou, 2010). That is, during the implementation of the original schedule, making adjustment to it in time according to the real-time status of pipeline and depots and market demand. Cafaro and Cerdá (2008) developed an efficient framework for the dynamic scheduling of pipelines over a multi-period moving horizon. The idea of their research is to execute the schedule for only one period, and the period will move forward as the current period ends. Then, the schedule will be reset based on the new period and new data. Rolling scheduling model can adjust the schedule in time and actively according to the operation state of pipelines and actual situation of market, and can make contributions to the development of smart scheduling of pipelines in the future. However, the existing research is limited to the rolling generation of aggregate schedule for straight pipelines.

3.1.2. Scheduling under uncertain environment

Deterministic scheduling models have certain advantages when the market environment is stable and predictable. However, in actual production, the emergencies, such as demand fluctuation, equipment failure, supply interruption occur occasionally, which may make the deterministic schedule no longer feasible. To improve the robustness of schedule, decrease its adjustment frequency, so as to make the obtained schedule still feasible within a certain fluctuation range. It is necessary to take the possible risks in pipeline operation into consideration before scheduling, and then establishing the scheduling model with coupled uncertainties.

Currently, the related studies mainly focus on the planning and resource allocation of refined product supply chain under uncertainties at the strategic and tactical levels. The existing research generally adopts fuzzy programming (Ghatee and Hashemi, 2009), stochastic programming (Lima et al., 2018), scenario-based method (Wang et al., 2019) and robust optimization (Ribas et al., 2010; Moradi and Mirhassani, 2016) to deal with the system uncertainties. Escudero and Dempster introduced the uncertainty optimization theory into the planning problem of refined product supply chain early. Based on the deterministic logistics optimization model, Escudero et al. (1999) proposed a stochastic programming model for the optimization of a multiperiod supply, transformation and distribution scheduling problem under uncertainties on the product demand, spot supply cost and spot selling price. However, their research focused on the description of proposed model, lack of the application of the real case. On the basis of Escudero's research, Dempster et al. (2000) assumed that product prices and costs follow Brownian motion processes, and established a scenario-based stochastic programming model. In their research, the difficulty of solving the stochastic programming model with uncertainty was discussed. Considering oil price uncertainty and demand uncertainty, Lima et al. (2018) put forward a multistage stochastic programming to solve the optimal planning of downstream oil supply chain. As the uncertainty leads to a large-scale optimization problem, a scenario reduction approach is adopted to decrease the problem size and improve the computational performance.

However, there are few studies on the robust optimization of pipeline scheduling considering the detailed technology at the operational level. Based on the deterministic scheduling model, Moradi and Mirhassani (2016) established the demand uncertainty set and adopted Γ-robustness approach to extend the deterministic model to its robust counterpart. Then, they applied it to the scheduling of a straight pipeline with single source and distribution center. The results indicated that by choosing the proper conservatism level, a good solution could be achieved that remains feasible for almost all scenarios. Their another finding was that the complexity of model would not change significantly through increasing the budget of robustness. Subsequently, Asl and Mirhassani (2019) attributed the impact of pump failure or pipeline interruption on the schedule to the influence of flowrate uncertainty on the schedule, and then established a two-stage mixed integer programming (MILP) model to solve the pipeline scheduling problem under flowrate uncertainty. To deal with the large-scale optimization problem caused by uncertainty, they proposed a method that combined the sample average approximation with Benders decomposition approach.

3.2. Research objects

After selecting the scheduling mode of pipelines, it needs to determine the accuracy of schedule, the topology and operation constraints of pipelines, so as to further determine the decision variables and constraints involved in the scheduling model.

3.2.1. The topology of pipelines

As the topology of multiproduct pipelines becomes more complicated, the research object of this field is gradually changed from straight pipelines to complex pipeline networks. The research on scheduling of straight pipelines include the single-source pipelines with single distribution center (Relvas et al., 2006; Cafaro and Cerdá, 2008), the single-source pipelines with multiple terminals (Cafaro and Cerdá, 2004; Cafaro et al., 2011), and the multisource pipelines (Cafaro et al., 2015; Liao et al., 2019a; Cafaro and Cerdá, 2010a). The research on the pipeline networks covers tree-structure pipeline networks (Liao et al., 2019b; Cafaro and Cerdá, 2010b; MirHassani and Jahromi, 2011) and mesh-structure pipeline networks (Liao et al., 2019c; Herrán et al., 2012; Cafaro and Cerdá, 2012). The topology of the above pipeline systems is shown in Fig. 7. Due to the simple topology of single-source pipelines, it is easy to establish the scheduling model and realize the batch tracking, thus the research has been mature. As for the multisource pipelines, because there are intermediate sources along the pipeline, their pumping operations make the batch numbering method in the research of single-source pipelines no longer applicable, which increases the difficulty of batch tracking. The existing studies generally define empty batches between the old batches that already in the line at the start of the scheduling horizon, so as to make it possible for an intermediate source to pump new products into the pipeline and modify the initial product sequence. However, the number of empty batches and their locations will affect the computational performance and quality of schedule, so it is necessary to manually select the appropriate number and location (Cafaro and Cerdá, 2009). To solve the above issue, Liao et al. (2019a) divided the pipeline into several sub lines by taking the intermediate sources as the nodes, and developed a line batch numbering method. In this method, the batch is marked by the line number and the batch number. It allows the batch number assigned to a product to change when crossing lines.

Through the junctions or dual-purpose depots, multiple pipelines can be connected to form the network. The complexity of the scheduling of a pipeline network is determined by its topology and the scale of pipelines it involved. To reduce the difficulty of solving such issues, the existing research generally adopts the splitting method, which takes the junctions or dual-purpose depots as the nodes to divide the network into several straight pipelines (Liao et al., 2019b; Liao et al., 2019c; Cafaro and Cerdá, 2010b; MirHassani and Jahromi, 2011; Cafaro and Cerdá, 2012). Compared with the scheduling of straight pipelines, the difficulties of the research on the scheduling of networks include the following two aspects: batch tracking and the mathematical formulation of the operation at the intermediate junctions. The former can be solved through predefining the empty batches or adopting the line batch numbering method. Liao et al. (2019b; 2019c) used the above methods to track the batches, and obtained the schedules of the branched pipeline system and mesh-structure pipeline network respectively. For the latter, the existing research generally introduces inventory management to realize the overall consideration of upstream and downstream pipelines.

According to the literature review, it is found that most of the existing studies are on the scheduling of small-scale pipelines and networks, and how to improve the computational performance of the scheduling of large-scale pipelines or networks is a hot topic in the future. Furthermore, as the vital nodes connecting upstream and downstream pipelines, the dual-purpose depots play an important role in the scheduling of pipeline networks. Most of the existing research considers the inventory limitations of the dual-purpose depots, or sets different pumping and delivery flowrates for specific product, but ignores the influence of the loading and unloading operations of tanks on the schedule. The reasonable connection between the schedules of pipelines and depots is not fully solved. If the model only considers the injection and delivery schedules of depots and is not accurate to the tanks, the schedule of the pipeline network may not be feasible at the operation level of tanks. That is, there is no feasible loading and unloading schedules for the tanks. Therefore, the research on the scheduling of pipeline net-

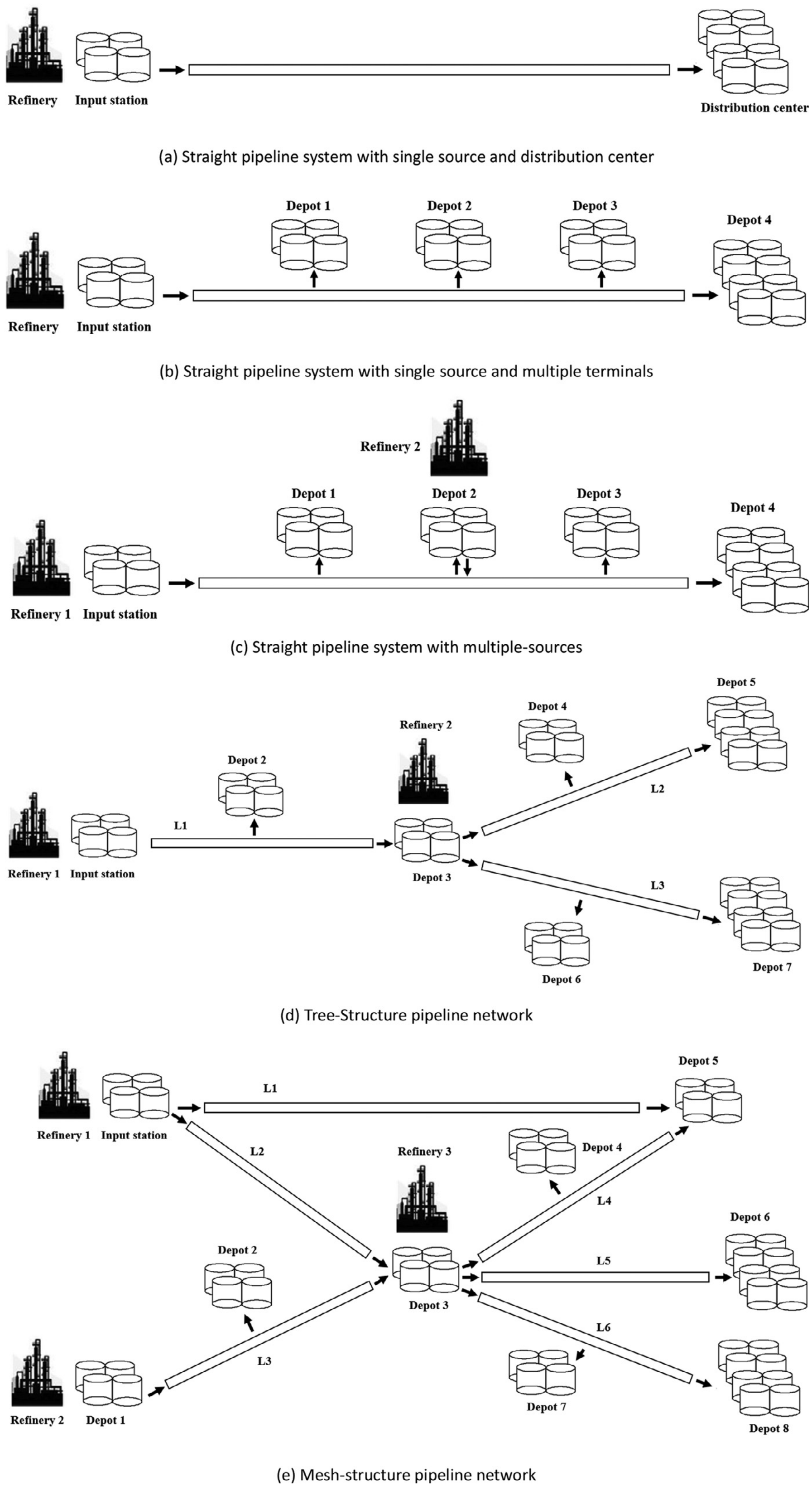

Fig. 7. The topology of typical pipeline systems.

works with full consideration of the operation technology of tanks at dual-purpose depots is also one of the further directions.

3.2.2. Accuracy of schedule

A complete schedule of a multiproduct pipeline should include the injection schedule of input station, the injection or delivery schedules of depots. Many scholars have studied the approximate scheduling and detailed scheduling of pipelines successively (Cafaro and Cerdá, 2004; Cafaro et al., 2011; Relvas et al., 2006; Rejowski Jr. and Pinto, 2003). The difference of the two types of schedules is that the aggregate schedule only contains the types and volume of refined products injected or delivered at each depot during each interval, but does not give the specific time and flowrate of each operation. Aiming at the scheduling of a straight pipeline system receiving a number of liquid products from a single refinery to distribute them among several depots, Rejowski Jr. and Pinto (2003) and Cafaro and Cerdá (2004) developed discrete and continuous MILP formulations to obtain the optimal schedule respectively. Then, Cafaro and Cerdá (2010a; 2010b; 2012), extended the studies to the multisource pipeline, tree-structure pipeline network and mesh-structure pipeline network.

Because the aggregate schedule is too rough, the schedulers cannot use it to guide the actual production and operation of pipelines. Therefore, a series of studies on detailed scheduling of pipelines have been carried out (Cafaro et al., 2011; Cafaro et al., 2012; Relvas et al., 2006; Cafaro and Cerdá, 2008; Cafaro et al., 2015). In detailed scheduling models, the time interval is divided more detailed, and the flowrate constraints are considered more strictly. Since the scheduling problem size is related to the complexity of pipeline topology, complex structure is more likely to lead to approximate scheduling model, so as to have a compromise between problem size and computational performance. Therefore, the previous work on the detailed scheduling models mainly focused on the pipelines with simple topology. Aiming at the scheduling of straight pipeline system with single source and distribution center, Relvas et al. (2006) and Cafaro and Cerdá (2008) proposed efficient MILP models respectively, which could make a detailed schedule at once. Later, with the further improvement of modeling and solving technology, the research objects of detailed scheduling models are gradually extended to the pipelines with complex structure (Cafaro et al., 2015; Liao et al., 2019c; Cafaro et al., 2011; Liao, 2018).

In the existing research, there are two methods generally adopted to obtain the detailed schedule. One is to directly establish a detailed scheduling model, the other is to develop the aggregate scheduling model and detailed scheduling model respectively by using the decomposition strategy. The detailed scheduling models were put forward and solved through the classic optimization method respectively (Chen et al., 2019; Zhang et al., 2016). Finally, the detailed schedule of each depot along the pipeline during the scheduling horizon can be successfully worked out. Cafaro et al. (2011; 2012) established two scheduling models respectively. In their study, the first model was solved to obtain the aggregate schedule which was then taken into the second model to work out the detailed schedule. Currently, the generation of detailed schedule is a hot spot in the research of multiproduct pipeline scheduling, because the detailed schedule can satisfy the actual production requirement.

3.2.3. Operation constraints

With the development of the research on multiproduct pipeline scheduling, more and more studies have introduced many operation constraints to describe the actual operation process of pipelines. From the perspective of depot functions, the following two types of problems have been widely studied. One is to consider that the depots along the pipeline have a single function, that is, the depots can only carry out injection operation or delivery operation (Cafaro and Cerdá, 2004; Zhang et al., 2016; Zhang et al., 2017; Cafaro et al., 2011; Cafaro and Cerdá, 2010a). The other is to consider that the depots have the above two functions, that is, they are capable of receiving products from the pipeline as a destination node and also pumping products into the pipeline as a source node (Cafaro et al., 2015; Liao et al., 2019a; Liao et al., 2019c). In terms of delivery operation, the early research assumed that at most one depot can receive products from the pipeline during one interval (Cafaro et al., 2011). However, such operations would inevitably rise the number of stoppage in pipeline segments, which is not consistent with the actual operation. Aiming at this problem, Cafaro et al. (2012) improved the model in the above research and allowed multiple depots to delivery products simultaneously. In terms of injection operation, for the scheduling of multiproduct pipelines with multiple sources, Cafaro and Cerdá (2009) assumed that at most one source can pump products into the pipeline at any time interval, while the drawback was successfully overcame in Cafaro and Cerdá (2010a). Then, such as pipeline shutdown, tank maintenance, pipeline operation stability are also considered in the study of this kind of issue.

3.2.4. Inventory management

The inventory variation of depots during the scheduling horizon may affect the solution of scheduling models. Therefore, inventory management should be taken into consideration when establishing the scheduling model. Some studies did not consider the impact of the inventory variation on the schedule, their ideas were to ensure that the products can be timely delivered to the depots when their inventory was at the minimum level. For instance, Zhang et al. (2016; 2017; 2018) carried out a series of studies on detailed scheduling of multiproduct pipeline with single source and multiple delivery terminals. In their research, they did not take inventory variation during the scheduling cycle into consideration, but gave an assumption that the depots had enough capacity to receive products.

There are other studies provide an assumption that all tanks that store the same product at a depot are considered as an aggregate tank. The sum of inventory limitations of all tanks is regarded as the inventory limitations of the depot. Rejowski Jr. et al. (2003); Cafaro and Cerdá (2004); Liao et al. (2019a; 2019b); Mostafaei et al. (2021b) introduced the maximum and minimum limitations of inventory into the models, and simultaneously realized the scheduling optimization of multiproduct pipelines and inventory management of depots. However, in Liao et al. (2019a), empty inventory was allowed, which was inconsistent with the actual operation of the depot. Subsequently, Liao et al. (2019c) added ending inventory limitation to the model. That is, at the end of the scheduling horizon, there should be enough inventory to not compromise the run for the next planning period. Meira et al. (2021) considered rigorous inventory management for each product at each depot. In their research, the inventory range of each depot was divided into five levels. Besides the physical limits, each tank was also set with operational range and target range to assist the inventory control. In this way, the inventory of each depot can always be kept within the safety level during the horizon, and the existing inventory can be used to protect the product demand of downstream market when the emergencies occur. Different from the above studies, Yu et al. (2020) set the feasible range for each tank at each depot.

In addition to inventory limitations, Relvas et al. (2006) and Dimas et al. (2018) also introduced settling time constraint into the models. This constraint ensures that simultaneous loading and unloading do not occur for tanks at the depot before the product is transferred to downstream market. Then, Relvas et al. (2007) improved their model in Relvas et al. (2006) by assuming that each product has different settling time at the depot.

3.3. Modeling methods

If the scheduling mode, topology, operation constraints and accuracy of schedule are determined, the time and volume representations of the scheduling model could be further determined.

3.3.1. Time representation

To clearly describe the delivery and injection operations performed by depots within the scheduling horizon, it is necessary to introduce the time representation when establishing a scheduling model. Time representation of scheduling models can be classified into discrete-time representation (Chen et al., 2017; Rejowski Jr. and Pinto, 2003; Herrán et al., 2010) and continuous-time representation (Cafaro and Cerdá, 2004; Rejowski and Pinto, 2008; Cafaro and Cerdá, 2010a; Castro and Mostafaei, 2017a).

In discrete-time expression, the time horizon is divided into several intervals with known size. The corresponding time nodes of each interval are taken as the event points that each batch just arrives at the downstream depots or the depots start to carry out operations. Rejowski Jr. and Pinto (2003) firstly developed a scheduling model by using discrete-time representation, in which the time horizon was divided through the event points that pumping operation of refinery and delivery operation of depots occurred. Discrete-time models make it much simpler to treat complicated constraints and the relationship of decision variables. Since the time nodes are known parameters, the models do not need to introduce nonlinear term when solving scheduling problems considering time-varying price (Relvas et al., 2013). Moreover, flowrate and volume are both regarded as the decision variables of the scheduling models, so it can handle the flowrate fluctuation and avoid frequent changes in flowrate (Liao et al., 2018; Chen et al., 2017). However, discrete-time models also bring some limitations when facing a long-term scheduling. If the length of time interval is long, it may lead to poor optimality of solution. If the length of time interval is short, it will cause poor computational performance due to the use of more intervals.

The continuous-time formulation takes the time nodes of critical events as the basis for dividing the time horizon. In this way, the starting and ending time nodes of each interval are set as variables. Although continuous-time models make the model logic tend to be complicated, exact product location and operation time can be tracked using fewer intervals than its discrete counterpart. It focuses more on the major changes of operations that occur during the horizon. Cafaro and Cerdá (2004) first proposed the continuous-time model. In their model, they divided the horizon through the starting and ending time nodes of pumping operation at input station. Compared with the discrete-time models, the continuous-time models can use fewer variables and constraints for the same scheduling problem, showing the better performance on computational scale and time (Mostafaei et al., 2021b).

3.3.2. Volume representation

Similar to the time representation, the volume representation of scheduling models can also be divided into discrete-volume representation and continuous-volume representation.

Discrete-volume formulation is also developed in Rejowski Jr. and Pinto (2003). In this formulation, pipeline is segregated into several packs according to the specified volume, and each pack only contains one product at any time. Batch tracking can be achieved by updating the product contained in each pack with time. The idea of this representation is that during an interval, if the products are moving forward in the pipeline, at the end of the interval, the product contained in each pack can successively transfer to the nearest pack or depot downstream. During any intervals, the input station can pump at most one type of product, and its volume can only be equal to the volume of the nearest pack to the input station. The depots along the pipeline can also only deliver the product from the nearest pack upstream, its volume should be equal to the volume of the pack (MirHassani and Ghorbanalizadeh, 2008; Herrán et al., 2010).

Continuous-volume representation is subdivided into batch-centric representation (Cafaro and Cerdá, 2004; Castro and Mostafaei, 2019; Relvas et al., 2006; Cafaro and Cerdá, 2010a) and product-centric representation (Castro and Mostafaei, 2017a; Castro, 2017b). In the former, products at the input station are converted into batches when pumped into the pipeline and back to products when delivered to depots. It ranks batches from largest to smallest in order based on flow direction, that is, the earlier the product is injected into the pipeline, the smaller the number is. In batch-centric formulations, the initial status of the pipeline and the total number of batches need to be prior defined. The seminal paper was developed by Cafaro and Cerdá (2004). Then, batch-centric formulations have been used by other research groups and extended to pipeline systems of different structures (Mostafaei et al., 2021a; MirHassani and Jahromi, 2011; Cafaro and Cerdá, 2012). The remarkable advantage of batch-centric models is that they need fewer time intervals to represent a schedule, which can be translated into better computational performance (Mostafaei et al., 2021b). However, batch-centric models also have their own limitations: (a) The definition of the total number of batches and the initial pipeline status are important parameters affecting solution optimality and computational performance, especially for the pipeline systems with intermediate sources. (b) The existence of empty batches in the batch sequence makes it much more difficult to enforce forbidden product sequences. (c) Under the different operation constraints, the flow direction of pipeline will change several times during a scheduling horizon, which makes it difficult to implement batch tracking with a fixed number.

Product-centric models do not need to postulate the initial status of pipeline and the total number of batches beforehand. Castro et al. (Castro and Mostafaei, 2017a; Castro, 2017b) was the first to develop a product-centric formulation that could tackle the scheduling of all types of pipeline systems. In their model, the whole pipeline system was regarded as a set of interconnected segments that can operate in both flow directions. They provided assumptions that: (a) At most one batch per product can exist inside a segment during an interval. (b) Multiple products cannot enter and leave a segment during an interval. This formulation does not sort batches by the fixed number, and realizes the batch tracking of multiproduct pipelines with multiple sources and dual flow directions. However, product-centric models also have disadvantages: (a) The first assumption may lead to an infeasible MILP for a feasible instance. (b) The second assumption may cause more time intervals to be used to find the optimal solution (Mostafaei et al., 2021b).

3.4. Solution strategies

When the contents of Section 3.1 to Section 3.3 are determined, a scheduling model can be developed, which can be solved through classic optimization algorithms, heuristic algorithms or meta-heuristic algorithms.

3.4.1. Classic optimization algorithms

The multiproduct pipeline scheduling problems may be formulated as linear or nonlinear optimization problems. Depending on the formulation of the problem, mixed integer linear programming (MILP) model or mixed integer nonlinear programming (MINLP) model may be used (Cafaro and Cerdá, 2004; Zhang et al., 2017; Cafaro et al., 2015; Relvas et al., 2013). The above models can be solved through the commercial solvers, such as CPLEX, GUROBI and so on. The algorithms embedded in the above solvers involve simplex algorithm, branch and bound algorithm and cutting plane method, etc. These algorithms search for the optimal solution of the scheduling model from the global perspective, which can guarantee the global optimality of the solution. However, the global search methods also make the time and space complexity of the model increase greatly. For instance, when the number of depots along the multiproduct pipeline or the batches is too large and the scheduling horizon is too long, the scale of the model will grow exponentially. At this time, if the commercial solvers are still used to solve the scheduling model, it is difficult to obtain a reasonable solution at a given time (Chen et al., 2017).

3.4.2. Heuristic algorithms

Heuristic algorithms refer to the existing mature algorithms, such as greedy algorithm, priority algorithm and depth-first search algorithm, or the methods proposed according to the scheduling experience of pipeline operators (Cafaro et al., 2011; Liao, 2018; MirHassani and BeheshtiAsl, 2013). The algorithms can effectively reduce the solution space of the studied problem and provide a feasible solution with great computational performance. Their advantage is that it can still obtain a satisfactory schedule in an acceptable time when facing a large-scale scheduling problem. According to the experience of pipeline operators, Liao et al. (2018) proposed a novel depth-first search algorithm based on flowrate ratio to deal with the detailed scheduling of a pipeline with multiple pump stations. Chen et al. (2017) summarized a set of heuristic rules based on the historical schedules, and then put forward an algorithm for optimizing the delivery operations of multiproduct pipelines. Through applying it to solve the scheduling problem of pipelines with different number of depots, the results showed that the schedule of each pipeline can be obtained within the given time, and its performance on computational effect and time are better than the solutions solved by commercial solvers. Although heuristic algorithms have some advantages in solving large-scale scheduling problems, the empirical rules of each kind of problems are not completely consistent, so the algorithms are not universal.

3.4.3. Meta-heuristic algorithms

Meta-heuristic algorithms include particle swarm optimization(PSO) algorithm, ant colony optimization(ACO) algorithm, genetic algorithm(GA) and simulated annealing(SA) algorithm. They can be used to solve scheduling problems in multiple stages. The process of applying this solution strategy to deal with the scheduling problem involves two steps. Firstly, based on decomposition strategy, the original problem is divided into several sub-problems which then can be solved by using the above meta-heuristic algorithms to obtain some key variables, such as the batch sequence and batch arrival time. Then, based on the obtained variables, the other problems can be solved by commercial solvers. In this strategy, the objective function of the model is generally set as the fitness function of the meta-heuristic algorithm. Zhang et al. (2016) decomposed the scheduling problem into two sub-problems, and used ACO algorithm to solve the first sub-problem to obtain the sequence of time nodes. Then, they took the objective function of the scheduling model established for the second sub-problem as the fitness function of ACO. The obtained time nodes were substituted into the model, and the model would be solved by using branch-and-bound method. Through the iteration, the optimal schedule will be output until the model converges. Chen et al. (2017) directly used SA algorithm to optimize the schedule of multiproduct pipelines. In their research, the idea of parallel computing was introduced into the algorithm to improve the construction strategy of the initial schedule. Although the meta-heuristic algorithms can solve large-scale scheduling problems, they also have the following disadvantages. One is that this strategy cannot guarantee the optimality of schedule, that is, the result may converge to a local optimal solution. The other is that this strategy cannot guarantee the high efficiency of the algorithm. The algorithm may need to iterate hundreds or even thousands of times to converge, and each iteration requires a highly complex calculation.

3.4.4. Data-driven methods

With the development of data science and machine learning, some studies introduce the data-driven methods into the field of multiproduct pipeline scheduling, which enriches the solution approaches of scheduling problems (Liao et al., 2018; Zhang et al., 2018; Liao et al., 2019). The methods attempt to fully learn and utilize the historical schedules of pipelines, and reduce the solution time on the basis of efficient learning of historical data. In the process of using the meta-heuristic algorithms to solve the scheduling model, if there is a big difference between the initial solution and the optimal solution, the solving time may be too long. However, in the actual operation of a multiproduct pipeline, if there is no significant difference in the supply scheme, demand scheme and initial pipeline state, then a new schedule to be developed will not be too different from historical schedules. Therefore, historical schedules can be recorded while making a schedule each time. When a new schedule needs to be developed, the closest historical schedule can be found by comparing such known parameters of the model, and then it can be used as the initial solution of the meta-heuristic algorithm. Based on the above analysis, Zhang et al. (2018) adopted fuzzy clustering method to find the closest schedule from the schedule database. The time nodes of the closest schedule were selected as the initial solution of the new schedule, so as to accelerate the convergence speed of the algorithm and improve the calculation effect. Compared with the traditional solution methods, the data-driven methods can make full use of the historical schedules of the pipeline and greatly reduce the solution time. It will be one of the future research directions.

4. Discussion and future directions

The research on multiproduct pipeline scheduling is relative mature. Based on comparisons between the related papers, some suggestions for future research are provided, which are hopefully useful for further progress in this field.

(1) As the bridges of upstream and downstream pipelines, dual-purpose depots will play an important role in the operation of multiproduct pipeline networks. Currently, most of the existing studies mainly focus on modeling methods and solution strategies of the scheduling of pipeline networks with complex structures. They only consider the inventory management of dual-purpose depots, or set different pumping and delivery flowrates for specific product, but ignore the influence of the loading and unloading operations of tanks on the schedule. Therefore, it is necessary to carry out the research on the scheduling of pipeline networks considering the operation technology of tanks at dual-purpose depots.

(2) The improvement of interconnection among pipelines aggravates the difficulty of the scheduling of pipeline networks. At present, most effective scheduling methods are applied to small-scale pipeline networks, which cannot meet the timeliness requirements of the scheduling of large-scale pipeline networks. Therefore, it can develop an efficient solution method based on machine learning in combination with the historical schedules of pipelines, so as to realize the rapid preparation of schedules of large-scale pipeline networks.

(3) At present, the existing studies mainly focus on the static scheduling, but the research on dynamic scheduling is still in the preliminary stage, which is limited to the rolling generation of the aggregate schedule of straight pipelines. In the future, the research on the active and online scheduling can be further developed. Based on the historical data of inventory of depots, the accurate prediction for product demand of depots can be carried out. At the same time, combining with the real-time data transmitted through Supervisory Control and Data Acquisition (SCADA) system, the active and online scheduling model coupled with the trend prediction of product supply and demand can be developed. Through this model, the inventory risk can be dynamically evaluated within the rolling cycle and the optimal detailed schedule can be generated. This method can provide the dynamic prediction, risk evaluation, result feedback and global adjustment for the pipeline network, and may become a decision tool for smart scheduling of multiproduct pipelines.

(4) The multiproduct pipeline system has strong uncertainties, which will make the deterministic schedule no longer feasible. Considering robustness in the scheduling model can reduce the risk caused by uncertain factors and the number of schedule adjustment, so that the schedule can still meet the market requirements within a certain range of demand. However, most of the existing studies concentrate

on the optimization of refined product supply chain under uncertainties, while the studies on the robust optimization of pipeline scheduling focus on the pipeline systems with single source and distribution center. It is necessary to combine the uncertainty optimization theory to extend the research to the pipeline systems with complex structures.

5. Conclusion

This paper selects multiproduct pipeline scheduling as the topic and reviews its research status. On the basis of extensive investigation of relevant literature, we count the number of published articles, the types of articles, the journals, the research groups and the latest work in this field, and summarize the general situation of this issue. Then, the bibliometric analysis method is used to carry out the co-occurrence analysis of the subjects involved in this issue. It is found that the multiproduct pipeline scheduling problem involves multiple subjects and belongs to the cross-disciplinary problem. Through the review of the existing studies, the research framework of this issue is constructed. Finally, the existing problems and future directions are discussed.

Declaration of Competing Interest

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

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