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Natural gas supply chain network design: An optimization-oriented review

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ABSTRACT

With the rapid development of natural gas industry, the optimal design is a key factor in improving the economic, environmental and social performance and efficiency of the natural gas supply chain. Therefore, it is necessary to conduct a comprehensive review of natural gas supply chain optimization problems to formulate future development plans. In this paper, we review the relevant literature on natural gas supply chain optimization, summarize the research progress of natural gas supply chain design optimization methods from the aspects of overall supply chain optimization, market operation and pricing mechanism optimization, pipe network transportation system optimization, and discuss the impact of natural gas market policy changes on supply chain optimization. Finally, the shortcomings of current research and the direction of future development are discussed.

Keywords: Natural gas pipeline network system, Natural gas market, Optimization model, Operations research

NONMENCLATURE

Abbreviations	
AHP	Analytic hierarchy method
EP	European Union
GA	Genetic algorithm
GP	Geometric programming
IAPSO	Inertial-adaptive particle swarm optimization
MFCP	Minimum fuel cost problem
MCP	Mixed complementarity problem
MILP	Mixed integer linear programming
MINLP	Mixed integer nonlinear programming
PSO	Particle swarm optimization
US	United states

1. INTRODUCTION AND MOTIVATION

Global energy demand has increased significantly in the past two decades, and it is estimated that from 2021 to 2040, global energy demand will increase continue [1]. In the energy industry of the new era, natural gas will gradually replace oil and coal, becoming the largest fossil energy source supporting economic development [2]. Gas production registered record-high volumetric increases in recent years and the average growth rate in the past 10 years is 2.3%, the united states (US) and Russia accounted for almost two-thirds of global growth. Similarly, gas consumption increased by 5.3%, with the US registering the strongest growth on record. Fig.1 shows the natural gas production and consumption by region from 2008 to 2018 (BP, 2019). Global forecasts of the level of natural gas reserves also clearly indicate that by 2035, natural gas will play an increasingly important role in supporting market growth [3]. Fig. 2 shows the distribution of proved reserves in 1998, 2008 and 2018, where the largest reserves are observed in the Middle East and the commonwealth of independent states (CIS). It can be seen that in the foreseeable future, natural gas consumption, production, and reserves will continue to increase steadily. This growth also means that more sophisticated optimization methods are needed to handle larger and more complex projects and ensure the economics of the supply chain system.

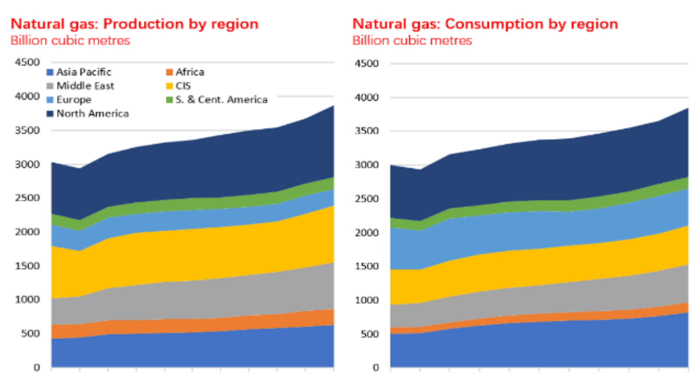

Fig. 1 The natural gas production and consumption by region from 2008 to 2018

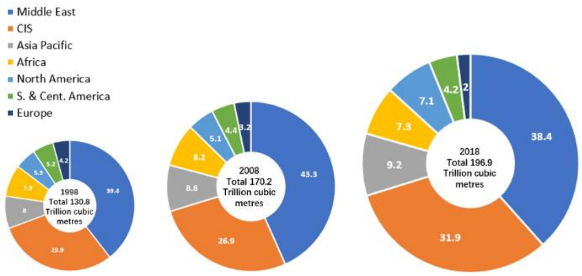

Fig. 2 Distribution of proved reserves in 1998, 2008 and 2018

The natural gas supply chain is divided into three parts: upstream, middle and downstream. The upstream is mainly for exploration and mining, the middle is for storage and transportation, and the downstream is for distributors to sell to the end-user market [4]. Supply chain network design is one of the most critical planning issues in supply chain management, and the concept of natural gas supply chain network design is often used to study the deployment of natural gas infrastructure [5]. To meet the needs of the rapid development of the natural gas industry, optimization techniques have been widely used in the study of natural gas supply chains, and many promising results have been achieved. To understand the development status of natural gas supply chain optimization more comprehensively, we summarized the related work of review articles. We found that most of the research on natural gas supply chain optimization focuses on natural gas market optimization [6], pricing decision-making [7], overall supply chain optimization [8], transportation system optimization [9], etc. In addition, the reform of the natural gas market also has an impact on the natural gas supply chain. There are limited reviews in the literature on natural gas supply chain optimization and do not cover all aspects of the issues it addresses. This study aims to review the optimization of the natural gas supply chain from different perspectives, and to provide suggestions and guidance for future research. The contributions of this study could be listed as follows:

(1) This review provides a complete and systematic analysis of 68 papers published in the field of natural gas supply chain optimization from 2000 to 2022.

(2) The optimization design of natural gas supply chain network design is reviewed from the aspects of overall optimization of the natural gas supply chain, optimization of market and pricing mechanism, and optimization of the transportation system. And analyzed the impact of market policy on the natural gas supply chain.

(3) The future development direction of natural gas supply chain optimization is prospected, and suggestions and guidance are provided for future research.

This paper is organized as follows. The methodology is provided in Section 2. Section 3 describes the overall optimization of the natural gas supply chain and the optimization of the natural gas market and pricing mechanism. The overview of the optimization of natural gas transportation systems is given in Section 4. Section 5 presents the natural gas supply chain optimization in the market environment. Finally, conclusions and directions for future research are drawn in Section 6.

2. METHODOLOGY

This paper will review and discuss related literature on natural gas supply chain network optimization from various aspects. The specific research framework is shown in fig.3 below. Firstly, we briefly introduce the natural gas supply chain and market mechanism, summarize the optimization of the overall supply chain, market operation and pricing mechanism, and then summarize the transportation optimization of the natural gas pipeline network from two aspects of design and operation, and then elaborate the optimization of natural gas supply chain considering relevant policies. Finally, we summarize the above three points and discuss and prospect the optimization of the natural gas supply chain network.

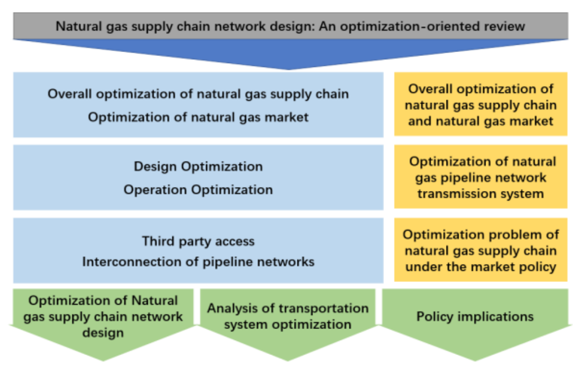

Fig. 3 Framework of optimization problems

The materials used in this paper are all literature related to natural gas supply chain network optimization published in famous journals from 2000 to 2022. Based on various journal articles, this paper reviews the optimization problem of the natural gas supply chain network. Fig.4 is our statistical analysis of journals that have cited more than one paper. Our research literature comes from 24 journals. From the bar chart, we can see that most of the journals are Applied Energy, Energy Policy, Journal of Natural Gas Science and Engineering, Energy and Energy Economics. Fig.5 displays the yearly distribution of these papers. We can see that the number of papers has an increasing trend, and in 2021 it reaches its highest value.

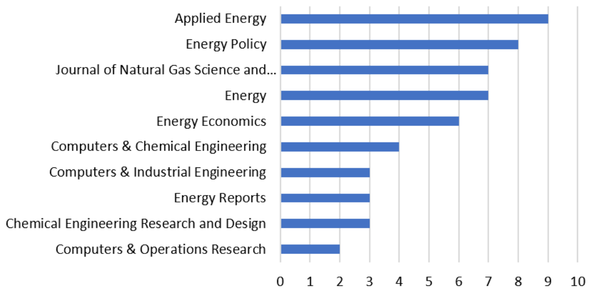

Fig.4 A statistical analysis of journals with more than 1 citation paper.

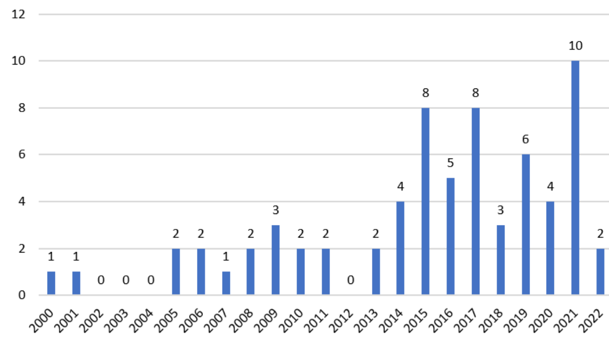

Fig.5 Timeline distribution of papers (68 papers: 2000–2022).

3. OVERALL OPTIMIZATION OF NATURAL GAS SUPPLY CHAIN AND NATURAL GAS MARKET

To study the optimization problem of natural gas supply chain, it is necessary to understand the composition of the natural gas supply chain and the operation, competition and pricing mechanism of natural gas market. Moreover, the natural gas supply chain is complex, and the optimization of the supply chain should also be studied from multiple perspectives.

3.1 Overall optimization of natural gas supply chain

Natural gas is delivered to consumers through channels including exploration, production, transportation, storage, and distribution stages. The schematic diagram of a simplified natural gas supply chain is shown in Fig. 6 [10]. The gas extracted from the gas well is acid gas, along with many impurities such as water, sand, carbon dioxide, etc., it needs to be processed, and part of it is provided to the injection customer. The processed natural gas is transported to the compressor station by the pipeline network, and part of the natural gas is again provided to the gas injection customers. The rest of the natural gas is transported to the city gate station through the pipeline network and distributed to various customers. Due to the pressure loss in the conveying process, this part of the loss is made up by the compressor station.

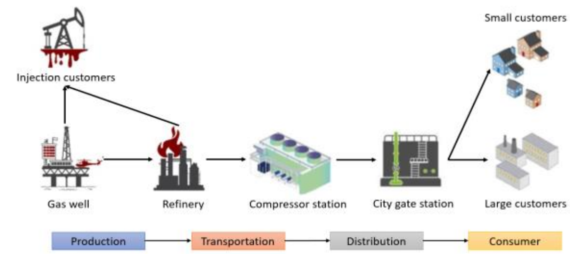

Fig.6 A schematic presentation of the natural gas supply chain.

In order to maximize the utilization efficiency of natural gas resources and ensure the economy of the supply chain system, the procurement, transportation and utilization of natural gas must be reasonably planned. However, the natural gas supply chain system has the characteristics of unbalanced supply and demand, large demand fluctuations, diverse transportation methods, and flexible transportation routes, which bring certain difficulties to the optimization of the natural gas supply chain system. Some scholars have studied the overall optimization of the natural gas supply chain. Zarei and Amin-Naseri [11] established a mixed integer linear programming (MILP) model to design and optimize the overall natural gas supply chain. The objective function of this model is to minimize the total cost, and it by optimizing gas flow between supply chain nodes, location distribution of facilities, pipeline routes and their capacity through pipelines, to minimize total costs. Samsatli [12] proposed a general MILP model for energy system networks considering transportation and storage facilities, which can determine the optimal network structure for short-term and long-term planning, respectively. In addition to a single economic goal, Bazyar et al. [10] established a multi-objective mathematical model with economic goals, environmental goals, and social goals to design a natural gas supply chain network focusing on sustainable development. Considering the uncertainty of model parameters, a four-stage solution method was used to solve the problem. In addition to the overall consideration of the supply chain, it is also necessary to optimize each link from different perspectives.

3.2 Optimization of natural gas market

Natural gas has commodity attributes, but it is different from general commodities. As non-renewable energy, its mining, sales, and storage are also affected by environmental and geographic factors [13]. Due to the uneven distribution and consumption of natural gas resources, the owner will determine the output and price of natural gas resources according to the market demand. This process is likely to form resource monopoly and monopoly pricing to get higher economic benefits [14]. In addition, another characteristic of the natural gas industry is that it requires a dedicated pipeline system for transportation. The monopoly of resource ownership and the characteristics of natural monopoly of pipeline transportation led to the early development of the natural gas market is generally operated by powerful state-owned enterprises, forming a monopoly or oligopoly market [15].

3.3 Research on natural gas market mechanism and optimization

Since the 1990s, natural gas markets around the world have experienced restructuring and deregulation [16]. For example, due to factors such as the restructuring of the natural gas market, the North American natural gas market has undergone major changes. The Federal Energy Regulatory Commission (FERC) issued order 637 in 1992, announcing that the operation mechanism of the natural gas market was transformed into an open transportation and sales model [17]. For the European Union (EU), the three natural gas orders (98/30/EC, 2003/55/EC, 2009/73/EC) have laid down steps to gradually integrate the natural gas market [18]. The purpose of issuing these orders is to increase competition in the natural gas market of EU countries and integrate them into the region, ultimately forming an EU-wide natural gas competition market [19]. With the advancement of natural gas marketization around the world, corresponding optimization models have emerged.

One of the early natural gas market models is peak-load pricing and investment policy model which maximizes social welfare in the Britain's domestic natural gas market developed by Tzoannos [20]. The model aims to determine the best seasonal electricity price structure for the UK natural gas sector based on experience, and to compare the best policy obtained with the current policy of the Britain domestic natural gas sector. In addition, the natural gas market can be seen as a game on the basic transportation network. Therefore, many scholars have applied the Cournot competition model and game theory to study the competition and market equilibrium between oligarchs in the natural gas market. Gabriel and Smeers [21] take advantage of the wealth of knowledge available in the electricity field, combined with game theory and other theories, to develop relevant models for restructuring the natural gas market. Holz et al. [22] proposed a European natural gas market supply model, which constructed the natural gas market as an upstream market for continuous export of natural gas to Europe and a two-stage game model for the downstream market for intra-European wholesale trade, and found two Cournot competition in the market is the most accurate representation of the European natural gas market today. Egging and Holz [23] regarded multiple producers, consumers and pipeline network operators as the main body to simulate the operation and game of the natural gas market, and analyze the natural gas production, consumption and trade patterns performed in the future. Feijoo et al. [14] established a game-planning model for the North American natural gas market to simulate natural gas production, consumption and trade decisions in the United States, Canada, and Mexico, and analyzed natural gas market reform pathways. Afterwards, more and more studies have focused on the optimization of natural gas market, which is used to guide the design and operation of natural gas supply chain system.

3.4 Research on natural gas pricing mechanism and optimization

The same as all commodities, the development and utilization of natural gas are also severely affected by its price. Reforming the natural gas pricing mechanism, preventing unreasonable natural gas consumption, and promoting the development of the natural gas industry are practical issues in formulating energy and environmental policies [24].

We can divide the national natural gas market into three geographic regions: The United States, Europe, and Asia. With significantly different demand-side factors, the three markets have different pricing mechanisms [25].

For the United States, its natural gas market has formed a sound market-oriented system, and the price of natural gas is determined entirely by market supply and demand [26]. A name called hub pricing that gas price is set by the market can perfectly describe the state of gas in the United States. In other words, the American natural gas pricing mechanism is built by the theory of supply and demand [27]. Once supply and demand do not match according to the market condition, natural gas prices will fall or rise [28].

The difference between the European natural gas market and the North American market is great. The natural gas import ratio in Western Europe is relatively large, and most of them are transported by pipeline and by sea. In a word, natural gas pricing in Europe is based on gasoline and fuel oil prices [29]. In the former Soviet Union, Russia is the largest producer and net exporter of natural gas. Its prices are controlled and sold far below market prices [30].

The East Asian market is priced mainly based on oil indexation [31]. In Japan, similar to Europe, crude oil is a vital element to form natural gas pricing in Japan, but it is not all. The risk aversion mechanism is used to better improve the market of natural gas. Once the price of petroleum is in an extreme situation, the risk aversion mechanism can prevent the price from fluctuation [32]. In China, due to the late start of the natural gas industry and the small market size, the natural gas pricing mechanism has been formulated in accordance with the planned economy thinking [31]. Generally speaking, natural gas pricing mainly adopts the strategy of government control as the mainstay and market regulation as the supplement [33]. Except for China and Japan, natural gas markets in developing countries such as India, Pakistan and Bangladesh have not formed, and their energy needs are still largely dependent on imports [34]. For these countries with imperfect natural gas markets, the pricing of natural gas is largely determined by oil indexation and government [25].

We can draw a conclusion of regional natural gas pricing in Table1. In the context of a sound market environment and abundant natural gas resources, the United States market is dominated by hub pricing and is affected by market supply and demand. Compared with the United States, the European market is more complex, and its high dependence on natural gas imports prevents Europe from turning to hub pricing as quickly as the United States, and needs to adjust slowly. For Asia, the oil index pricing model remains dominant and will be hard to change over the next few years.

Table 1 The conclusion of regional pricing mechanism of natural gas.

Region	Mechanisms	Features	Literature
America	Hub pricing	The price is decided by the gas-to-gas competition	Lin and Li, 2015; Ji et al., 2018; Brown and Krupnick, 2010
Europe	The period turns oil indexation to hub pricing	The price is decided by market and oil price together	Bastianin et al., 2019; Orlov, 2017
Asia	Oil indexation and government control	The price is decided by oil price, and government plays a critical role in deciding price	Siliverstovs et al., 2005; Lin and Li, 2021; Shi and Variam, 2017; Han et al., 2021

A reasonable natural gas pricing mechanism can guide the rational allocation of natural gas resources, promote operators to increase production and expand imports, and guide consumers to use natural gas rationally and economically. Many scholars have studied the optimization of natural gas supply chain from the perspective of natural gas pricing decision. Rioux et al. [35] assessed the impact of government pricing policies on the supply logistics of natural gas companies through a mixed-complementary problem model for the natural gas industry. Zarei et al. [36] proposed a new game-theoretic model to study competition among members of a multi-tier natural gas supply chain to determine the optimal price among supply chain members. Tookanlou et al. [37] determined the optimal peak-valley and off-peak-valley electricity prices of natural gas in each season in a combined heat and power system based on a particle swarm optimization algorithm based on two-layer programming.

The aforementioned research on the natural gas market and pricing mechanism provides a theoretical basis for constructing a natural gas supply chain optimization model, especially for empirical research, the assumption of a competitive market is very necessary.

4. OPTIMIZATION OF NATURAL GAS PIPELINE NETWORK TRANSPORTATION SYSTEM

The natural gas transportation system is important in the natural gas supply chain, and the pipeline transportation is the most economical and efficient transportation method. Designing and operating an efficient natural gas pipeline network is very important to meet customer needs in a timely manner and minimize costs. In recent years, many scholars have studied the transportation optimization of natural gas pipeline networks. In general, the optimization problems can be classified into operation problems and design problems [38]. Design optimization and operation optimization can be further classified based on the objective functions as shown in Fig. 7.

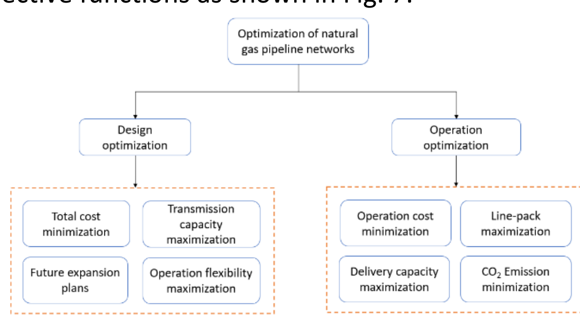

Fig.7 Classification of optimization in natural gas networks

4.1 Optimization of natural gas pipeline network design

The optimization for design problems focuses on the type, location, and installation schedule of physical components, length of the pipeline, pipe diameter, compressor station configuration and material selection. Kabirian and Hemmati [39] presented an integrated nonlinear optimization model, this model provided the best development plans (the type, location, and installation schedule of major physical components of a network including pipelines and compressor stations). And a heuristic random search optimization method is proposed to minimize the present value of operating and investment costs within the scope of long-term planning. Sanaye and Mahmoudimehr [40] considered a wide range of design parameters, proposed an optimization tool consisting of Genetic Algorithm (GA) and optimal properties of single pipelines to optimize the design parameters of a natural gas transmission pipeline with the goal of minimizing the sum of investment and operating costs. Hamedi et al. [41] built a single-objective, multi-period distribution planning mixed integer nonlinear programming (MINLP) model for natural gas supply chain, the objective of this model is to minimize all related costs of the power distribution system and the utilization of nominal capacity and operating capacity. Wang et al. [42] proposed a multi-period MILP model for the optimization of natural gas transmission pipeline network to determine the connection of pipeline and the construction location of compressor stations simultaneously, and it is solved by piece-wise linearization method.

It can be seen that most scholars take the optimization of design problems are minimizing investment and operating costs of infrastructure as objectives. In addition, many scholars use other optimization objectives to consider the design optimization problem. Alves et al. [43] proposed an optimization procedure as a tool to design and optimize natural gas pipeline transmission network, the two objectives considered aim to maximize the quantities of natural gas to be transported and to minimize the transportation cost. This study can enable decision-makers to make a trade-off between transportation volume and transportation cost, so as to find the best transportation scheme. Fodstad et al. [44] from the perspective of operational flexibility, a natural gas pipeline network model is set up with a system operator and a shipper in order to analyze whether the use of interruptible transportation services can improve the capacity utilization of the natural gas transportation network.

With the increasing demand for natural gas, natural gas network expansion has also become an important research content. Üster and Dilaveroğlu [45] proposed a new optimization method to help design a new natural gas transmission network or expand the existing network, while minimizing the total investment and operating costs, and developed an integrated large-scale MINLP model help to determine pipelines in the network, location and capacity of the compressor stations, timings of these installations in a multi-period planning horizon, and natural gas purchase and steady-state flow decisions for each period in the network. Chaudry et al. [46] established a network expansion planning model combined natural gas and electricity system, this model is expressed as an MINLP problem to minimize the cost of network operation and infrastructure expansion. And the expansion of the natural gas network is achieved through varying the pipe diameters of existing pipes, adding new assets such as pipes, compressors, and storage facilities.

4.2 Optimization of natural gas pipeline network operation

The optimization problem of natural gas pipeline network operation mainly focuses on the operation parameters of the pipeline network, and it considers different targets such as minimizing the fuel costs, maximizing the delivery capacity, minimizing greenhouse gas emission and so on.

4.2.1 Compressor station modeling

In the process of gas transportation in pipelines, there are pressure drops because of the friction between the inner surface of the pipeline and the gas. In order to ensure the normal supply of gas, the compressors along the pipeline are used to increase the pressure to compensate for the pressure drop. According to Demissie et al. [47], the operating cost of the compressor accounts for 25% to 50% of the company's total operating budget. Therefore, optimizing the compressor operation and minimizing the fuel consumed by the compressor stations are very important issues.

The minimum fuel cost problem (MFCP) has been studied by many scholars. Such as Wu et al. [48] thoroughly studied the mathematical structure of the compressor station and proposed a mathematical model of the problem, and solved the problem of minimizing the fuel cost by the compressor station drives the gas in the transmission network under the assumption of steady-state. These studies focused on the mathematical model of the compressor unit, and these optimization models are very complex, including nonlinearity and non-convexity, so are difficult to solve with feasible calculation methods. Methods have been developed including dynamic programming, gradient search, geometric programming approaches and so on [49].

For steady-state problems, one of the most successful techniques is dynamic programming. Borraz-Sánchez and Haugland [50] took node pressure and flow as decision variables to study the problem of minimizing compressor fuel costs in natural gas transmission networks. Their contribution is to propose an adaptive discretization scheme and solve it through dynamic programming. Ríos-Mercado et al. [51] proposed a two-stage heuristic algorithm to solve the fuel cost minimization problem of a gas transmission system with a cyclic network topology. In the first stage, the gas flow variable is fixed, and the optimal pressure variable is found via dynamic programming. In the second stage, the pressure variable is fixed, and an attempt is made to find a set of flow variables to improve the objective function by using the underlying network structure.

Many scholars have also studied the mixed integer nonlinear programming method. Chebouba et al. [52] proposed an ant colony optimization algorithm for stable flow gas pipeline operation to minimize power consumption and the number and pressure of compressors in each station as variables. And they found that compared with dynamic programming technology, the algorithm based on the ant colony element heuristic has better performance. Wu et al. [53] established a hybrid objective model with compressor switching constraints, aimed at balancing the maximum operation benefit and the maximum transmission amount. For this hybrid objective, the analytic hierarchy method (AHP) is used to determine the weight value of every single objective. Aiming at the nonlinear characteristic of the model, the inertial-adaptive particle swarm optimization (IAPSO) is used to solve it, this method can overcome the premature defects of the basic particle swarm optimization (PSO) algorithm.

In addition to the above two methods, Misra et al. [54] proposed a new geometric programming (GP) method to optimize compressor operation in natural gas pipelines. This method turns MFCP into a convex optimization problem. Compared with the traditional dynamic programming, the advantage of the GP method is that it does not having to discrete node pressure and compression ratio variables. Jin and Wojtanowicz [55] proposed a large-scale natural gas pipeline network optimization model in China, used penalty function method, pattern search, enumeration and non-sequential dynamic programming methods to decompose and optimize the entire network, integrate and optimize globally.

For time-related transient problems, transient models are more challenging because the control partial differential equations related to the gas system dynamics must be considered. Zuo et al. [56] studied the MFCP under unsteady states, use a linear function to approximate the energy consumption of the compressor unit under specific conditions, and then the compressor problem is described as a MILP model and solved by CPLEX. Domschke et al. [57] considered this problem as an MCFP with a nonlinear objective function and additional nonlinear constraints on the network arcs, and solved it by a combination of a new MILP method based on piecewise linearization and a classical sequential quadratic programming applied to the given combination constraints.

4.2.2 Other objective modeling

In addition to minimizing the operating cost of the compressor, many scholars have also considered other goals to simulate the problem of operating optimization. Carter et al. [58] described the noise optimization problem in the operation of gas pipelines. The solution method is implicit filtering, direct method and a new hybrid method of these methods. Fasihizadeh et al. [59] considered maximizing the pipeline delivery capacity, a simple network model was simulated using Simone simulation software, by selecting an appropriate number of compressors and adjusting the inlet pressure, the gas delivery flow can be optimized. At the same time, the cost can be reduced by reducing the gas consumption and running time of the compressor. Su et al. [38] considered the reliability of natural gas pipeline network operation while considering the lowest energy cost, and proposed a multi-objective optimization method to find an operation strategy that minimizes the risk of power demand and natural gas supply shortage, and solved by the NSGA-II algorithm. Liu et al. [60] considered the uncertainty of demand and the fluctuation of gas composition, studied the problem of minimizing cost under the two uncertainties, established a dynamic model with rigorous thermodynamic equations, and solved it with Monte Carlo simulation and robust optimization. Duan et al. [61] proposed a distributed optimization model of the integrated electricity and natural gas distribution network, considered the impact of uncertainty related to wind power, and used the ATC algorithm to solve the problem by introducing the coupling boundary consistency constraint. Yang et al. [62] based on the comprehensive consideration of the external costs of natural gas and other fossil fuels, proposed a new method for optimizing the regional distribution of natural gas. China has been used as an example to study the impact of external costs on the optimal allocation of natural gas.

Table 2 summarizes the research on optimization problems of natural gas pipeline network operation. Entries are first sorted by the classification of optimization, then by model state, and then by optimization objectives.

Table 2 Summary of research on optimization problems of natural gas pipeline network operation.

Work	Classification	Objective	Approach
Kabirian and Hemmati [39]	Design	Total costs	Heuristic algorithm
Wang et al [42]	Design	Total costs	Piecewise linearization
Sanaye and Mahmoudimehr,[40]	Design	Operation costs	Genetic Algorithm
Hamedi et al [41]	Design	Total costs and utilization	Hierarchical algorithm
Alves et al [43]	Design	System transmission capacity	Pareto optimality
Fodstad et al [44]	Design	Operation flexibility	Stochastic programming
Üster and Dilaveroğlu [45]	Design	Future expansion plans	Branch and bound
Borraz-Sánchez and Haugland [50]	Operation	Fuel cost	Dynamic programming
Chebouba et al [52]	Operation	Fuel cost	Ant colony
Wu et al [53]	Operation	Fuel cost	Particle swarm optimization
Misra et al [54]	Operation	Fuel cost	Geometric programming
Zuo et al [56]	Operation	Fuel cost	Branch and bound
Carter et al [58]	Operation	Noise	Implicit filtering
Fasihizadeh et al [59]	Operation	Delivery capacity	Simone software
Su et al [38]	Operation	Reliability	NSGA-II
Yang et al [62]	Operation	Emission	Branch and bound

5. OPTIMIZATION PROBLEM OF NATURAL GAS SUPPLY CHAIN UNDER THE MARKET POLICY

In section 4, we talked about the impact of the internal design and operation of the pipeline network on the natural gas pipeline network transportation system, such as how to control the node pressure to optimize the pipeline flow configuration, how to control the compressor operation to minimize the total cost. In addition, the natural gas market allocation mechanism also has a great impact on the natural gas supply chain. Therefore, it is also necessary to consider combining the physical elements of the pipe network with the market elements, as a whole supply chain for analysis and optimization.

Third-party access for natural gas infrastructure means that business entities operating and economically independent in this field have the right to enter and use various supply network facilities owned by other companies, thereby forming a freely competitive market. The interconnection of the natural gas pipeline network is to connect the existing pipelines to form a natural gas pipeline network system, realize the effective allocation of resources, transport natural gas to the place where it is needed, and realize the effective connection from supply to the market. From the perspective of the development process of countries with the mature natural gas market, free competitive pricing, pipeline network interconnection, and third-party access can improve the efficiency of market allocation, which is the only way to maturity in all aspect of the natural gas market [63].

Many scholars have analyzed the factors that affect the efficiency and economics of the natural gas allocation of the pipeline network system by simulating the flow configuration situation, and obtained the policy management enlightenment for optimizing the natural gas supply chain. Jing et al. [64] studied third-party access regulatory issues in China's natural gas market, based on mixed complementarity problem (MCP), constructed a natural gas market model with access conditions for third-party pipeline network operations, and prove that third-party access can bring great social benefits. Chen et al. [65] integrated the physical pipe network system and market economy elements, took maximization social welfare as the objective function, established a natural gas supply chain optimization model, maximized social welfare by increasing output at low-cost supply nodes or increasing supply to high priced demand nodes, which provides policy significance for natural gas pipeline network supervision. Although significant progress has been made in the liberalization of natural gas markets in some countries, certain key areas such as third-party access and pricing mechanisms are still controlled by the government. Based on this, Rioux et al. [35] established an MCP model for China's natural gas industry, evaluated the impact of government pricing policies and restricting third-party access to midstream infrastructure on profits in the natural gas supply chain, and the results show that both lifting the price caps and improving third party access I can reduce the total cost of the supply chain.

As a bridge between upstream resources and downstream markets, the development of the natural gas supply chain is dependent on natural gas infrastructures such as pipeline networks and underground natural gas storage. The construction of natural gas infrastructure directly determines the scale of the natural gas market. The operating mechanism of the natural gas market also affects the utilization rate of infrastructure. Avraam et al. [16] combined the natural gas consumption prediction model with the natural gas market model to simulate the natural gas system in North America, their results establish the impact of natural gas markets on natural gas infrastructure. Therefore, the development of the natural gas supply chain is inseparable from the infrastructure construction and interconnection of pipeline networks. At the same time, the impact of market developments on gas flows and physical market integration is also great. Dieckhöner et al. [63] analyzed various scenarios with a European natural gas infrastructure model to analyze the gas flows and market integration of the European market under different demand and pipeline interconnection scenarios. Based on these results, a conclusion can be drawn about the integration of the European market in the next decade. Australia's east coast natural gas market is facing the risk of high prices and energy shortages, Billimoria et al. [66] established a least-cost mixed-integer programming model to research the impact of market interconnectivity on long-term gas prices in Australia, and the model results show that improving network connectivity can provide continuous price reductions for the natural gas market. Mikolajková et al. [67] considered the supply of natural gas from external natural gas pipeline networks, a natural gas distribution pipeline network MINLP versatile model considering the interconnection of pipelines was developed. This model took the sum of the cost of natural gas compression, alternative fuels, and pipeline interconnection as the objective function, considered the flow and energy balance equations for the network nodes, determined the scale and operating conditions of the pipeline network and got the best interconnection results.

6. CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

With the rapid development of the natural gas industry, the network of the natural gas supply chain has become very complex, and the optimization of the natural gas supply chain design has also become a very important research topic. This paper summarizes the research progress of natural gas supply chain design optimization methods from the perspectives of overall optimization of natural gas supply chain, optimization of market operation and pricing mechanism, and optimization of pipeline network transport system, and discusses the impact of natural gas market policy changes on supply chain optimization. The conclusions and directions for future research are as follows:

(1) For overall supply chain optimization, most scholars have only considered a single economic objective, but in fact, a sustainable supply chain needs to integrate the consideration of economic, environmental and social objectives. Few papers have been able to present a multi-objective model that considers the above three aspects at present, therefore, developing a model that combines economic, environmental and social sustainability concepts is a future direction for researchers interested in the field of natural gas supply chain overall optimization

(2) The international natural gas market is at a special stage of development. With the completion of the natural gas market reforms in North America and the United Kingdom, European regions and Asian countries are also actively conducting reform attempts, gradually relaxing government intervention in the natural gas market, and establishing an operation and allocation mechanism suitable for the development of the natural gas market. The development of LNG makes the natural gas market globalize gradually, and a unified global market is the inevitable direction of future natural gas development.

(3) Natural gas pricing mechanisms are different from region to region. Under a free-market environment, the American market is dominated by hub pricing, Europe is converting oil indexation into market pricing, while Asia is strictly implementing oil indexation. For hub pricing, it is highly adaptable and can be fully integrated with the market economy, and it is a better market pricing mechanism. Therefore, there is still a long way to go for Asia and Europe to catch up with the American market.

(4) Many scholars have studied the optimization problem of the transportation system in the natural gas supply chain, it can be classified into operation problems and design problems. On the one hand, there are many solutions to the steady-state problem at present, and the most significant challenge facing the natural gas transportation industry is how to solve the transient model. For transient problems, decision variables are functions of time, which increases the number of variables and the complexity of the model. Work in this field is still in the development stage. On the other hand, a more comprehensive optimization framework should also be considered, comprehensive consideration of operating costs, supply reliability, greenhouse gas emissions and other factors, and to find better optimization algorithms. In conclusion, developing exact algorithms, such as decomposition-based algorithms or hybrid solution methods, is one of the most attractive research directions in the future.

(5) Since the reform of the natural gas market, governments of various countries have issued corresponding policies. Policies such as third-party access of infrastructure and the interconnection of pipeline networks have brought a good impact on the market, but at the same time, they have also aggravated the difficulty of the optimizations of pipe network system. Some scholars have studied the optimization of the natural gas supply chain under the influence of policy, but in this era of complex changes in the natural gas market, this is not enough. In addition, economic and political factors differ from country to country. Combining national gas markets, case studies of different countries can also be seen as another research opportunity in the future. We see this as a huge area of natural gas supply chain optimization.

In summary, this paper takes the optimization of natural gas supply chain as the research object, counts some work in this field on the basis of extensive access to relevant literature, summarizes the general situation of this problem, and discusses the existing problems and future development direction.

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