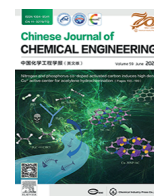




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The calculation and optimal allocation of transmission capacity in natural gas networks with MINLP models

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ABSTRACT

The transmission capacity of gas pipeline networks should be calculated and allocated to deal with the capacity booking with shippers. Technical capacities, which depend on the gas flow distribution at routes or interchange points, are calculated with a multiobjective optimization model and form a Pareto solution set in the entry/exit or point-to-point regime. Then, the commercial capacities, which can be directly applied in capacity booking, are calculated with single-objective optimization models that are transformed from the above multiobjective model based on three allocation rules and the demand of shippers. Next, peak-shaving capacities, which are daily oversupply or overdelivery amounts at inlets or deliveries, are calculated with two-stage transient optimization models. Considering the hydraulic process of a pipeline network and operating schemes of compressor stations, all the above models are mixed-integer nonlinear programming problems. Finally, a case study is made to demonstrate the ability of the models.

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1. Introduction

In an unbundled natural gas market, independent pipeline companies are obliged to provide the transmission capacity with gas networks to the shippers fairly and are not allowed to participate in natural gas trading. A capacity booking contract should be signed between the pipeline company and the shipper before gas transmission, in which the maximum daily throughput, inlets and (or) deliveries, period, and some other details are included. During the implementation of a contract, the shipper submits nominations no more than the specified maximum daily throughput at the specified inlet and (or) delivery, and the gas network is operated to transmit gas as the nominations. There are two popular regimes named point-to-point (P2P) and entry/exit (E/E) applied worldwide to determine how to specify injections and deliveries and how to charge shippers in the capacity booking. In the P2P regime, which is applied in the U.S., shippers specify injection and delivery points and are charged according to a flow route specified in a contract that is based on a physical network. Although the transmission capacity of a route between an entry and an exit is booked, an operator does not have to transport gas per that route. In contrast, an E/E regime, where injection and delivery capacities are booked and charged separately, and a gas transmission route is

not referenced in transmission contracts, is mostly applied in Europe. In the E/E regime, capacity booking is no longer based on a physical network. This network is a “black box” for shippers as it only contains inlets and outlets but not flow routes. The advantages and disadvantages of the two regimes from the perspective of the gas market are discussed [1–3]. Gas transmission businesses have recently been unbundled from integrated oil and gas companies in China, and a new national pipeline company named Pipe-China has been organized. Given these circumstances, a P2P tariff regime will be applied to long-distance transmission networks in China, while in regional networks, an E/E model will be considered.

The transmission capacity of a gas network, which is defined regardless of open access, is the maximum throughput that can be received, delivered, or passed through a point in unit time [4]. For a linear or branched pipeline, the maximum throughput of a trunkline is considered as the technical capacity of the pipeline [5,6]. The total throughput is defined as the technical capacity of a network, the maximum values of which are different when different entries/exits are specified for injection/delivery, and therefore, the technical capacity of a network is reported within an interval [7,8]. Previous research considered the effect of different distributions of flow at entries and exits on the total throughput for a branched pipeline. However, the interval of the maximum total throughput cannot reflect the specific effect of different points.

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Under an E/E regime, injection and delivery capacities are studied. The capacity defined by the U.S. Energy Information Administration in 1998, has been renamed the technical capacity [9]. In addition, firm and interruptible capacities are defined in these proposals as “gas transmission capacity contractually guaranteed by the transmission system operator” and “gas transmission capacity that can be interrupted by the transmission system operator according to the conditions stipulated in the transportation contract”, respectively. The firm and interruptible capacity definitions defined above were summarized as the commercial capacity [10]. This author also suggested that the technical capacity only depends on the physical structure and boundary conditions of a gas network, whereas the commercial capacity is allocated to shippers by a transmission operator according to the demand of shippers.

New problems arise when considering open access of a gas network. For the E/E regime, the following problems are presented for further research [11]: the validation of nominations (the daily amount of gas nominated by shippers), the verification of commercial capacities, the detection of technical capacities, and the topological extension of the network. The validation of nominations, which is a basic problem in capacity trading, determines whether a set of nominations can be satisfied by a gas network [12]. The computational complexity of the feasibility verification of commercial capacities with only passive elements in a gas network was studied [13,14]. The methods to verify commercial capacities were proposed as follows [15–17]. A variety of possible load conditions was proposed based on historical data, the current gas market, and artificial experience; then, a verification of the feasibility of these conditions under a physical gas network based on a steady-state optimization model was performed; finally, a load condition for the commercial gas transmission capacity was determined. The detection of technical capacities was proven to be an NP-hard problem [18]. These researchers also analyzed the technical capacities of a gas network with a classic linear flow model, simplifying this network as a capacitated network. The topological extension of a network focuses on the network design rather than the network operation, and will not be discussed here.

The above literature proves that the technical capacity is hard to solve considering the uncertainty of nominations. The verification method guarantees the feasibility of a commercial capacity allocation scheme, but not its optimality, which may lead to low utilization of a gas network. In addition, this method is not conducive for pipeline companies to analyze and optimize the operation status of a gas network. However, the calculated technical capacity or allocated commercial capacity of a gas network is not required to satisfy all the nominations all the time; instead, reaching a degree of reliability is adequate. Thus, the uncertainty of nominations is ignored in capacities calculation and allocation which are solved with a detailed mathematical model. The reliability of the commercial capacity can be verified considering the uncertainty of future nominations. The technical capacity of a gas network is described with a vector to illustrate the relation of the maximum flow at different entries and exits, and calculated with a multiobjective model. Moreover, the method proposed in this study shows the similarities and differences in the E/E and P2P regimes, which provides convenience for countries such as China, where both regimes can be applied. Finally, the short-term peak-shaving capacity, which is rarely considered in capacity research, is calculated with transient hydraulic optimization model in this paper.

A mathematical optimization model of a gas network consists of an objective function and multiple constraints on passive and active elements [19–22]. Compressor stations and valves are active elements [23], the operating states of which can be regulated by an operator. Entries, exits, and pipe segments are passive elements [20,24–26]. The variables of pressure, temperature, and flow are

continuous in the models, while the open/closed state of the valves and compressor stations should be expressed by discrete variables. An objective function is used to evaluate the operation status of a gas network. Consequently, a large-scale mathematical optimization model has difficulty finding an optimal or even feasible solution to a natural gas pipeline optimization problem, which includes discrete and continuous variables and linear and nonlinear constraints. Therefore, building models with appropriate precision and solving algorithms are critical for this type of gas network optimization problem.

This paper is organized as follows. The transmission capacity concepts, including the technical capacity, commercial capacity, and peak-shaving capacity, and their mathematical expressions and applications, are defined in Section 2. Section 3 mainly describes the mathematical models of the above problems, including constraints, objectives, formulations, and solution methods. In Section 4, a case study is applied to demonstrate the concept and method proposed. Finally, Section 5 concludes the research and provides some suggestions for future work.

2. Concepts of the Transmission Capacity of a Gas Network

Medium- and long-term gas transmission capacities of a pipeline network, which are reported in months, years, or longer amounts of time, can be calculated and allocated based on steady-state operating assumptions since the initial conditions have minimal impact on the capacity. Thus, technical and commercial capacities are studied based on a steady operation. Furthermore, the analysis of short-term peak-shaving capacity helps an operator improve transmission service and secure gas supply, providing additional peak-shaving services with a linepack. When calculating the short-term transmission capacity of a gas network, the initial flow state of the network and the unsteady operation process will have a nonnegligible impact on the injection and delivery capacities of the pipeline network. Thus, a transient optimization model is applied to calculate the peak-shaving capacity.

2.1. Technical and commercial capacity

In a gas network, entries/exits are not equivalent for both an operator and a shipper since a pipeline operator must inject/deliver gas in/from the points specified by a shipper. In addition, the maximum flow at different points of a network is always different for topological and hydraulic reasons. Therefore, it is not practical for capacity booking to represent the transmission capacity of a gas network using the maximum total flow through the network. Thus, in this paper, the technical and commercial capacities of a gas network are expressed by vectors, where each component denotes the flow at an inlet or outlet in an E/E regime to reflect the difference between inlets or outlets. In a P2P regime, matrices are applied to express the technical and commercial capacities of a gas network, and each component denotes a flow from an entry to an exit, where a row index denotes an entry and a column index denotes an exit. For convenient presentation, a capacity matrix can also be transformed into a vector. Suppose a gas network has n_1 entries and n_2 exits. Then, the technical and commercial capacity in an E/E regime can be expressed as $C_{n_1+n_2}$, while a P2P capacity can be expressed as $C_{n_1 \times n_2}$. The technical capacity of a pipeline is a maximum throughput vector within the operational constraints. Thus, the calculation of the technical capacities of a natural gas pipeline system can be transformed into a vector (multiobjective) optimization problem. In this problem the objectives are flows at different nodes or routes, the energy cost is not considered. The flows at entries or exits are usually mutually restrictive in a gas network system; thus, there is usually no such capacity vector in

which all elements reach the maximum value at the same time. Therefore, the technical capacities of a pipeline form a Pareto optimal solution set of a multiobjective problem to reflect the effect of the flow distribution on the capacity of a network.

The calculation and analysis of the technical capacity set find the upper and lower limits for the throughput of routes, entries or exits, and the gas network, providing references for gas transmission capacity allocation. In addition, the technical capacity can be used to analyze the relationship between flows at two entries/exits or in two gas transmission routes. Finally, the operating condition when a gas network reaches a technical capacity can be analyzed to find the factors that limit throughput, helping to determine the key to the extension and reconstruction of the network.

Because technical capacities cannot be directly applied in capacity booking, the demand of shippers and allocation rules should be taken into consideration to determine one Pareto solution as commercial capacity, which is published to shippers and used in booking directly to ensure the maximum utilization of a pipeline network while maximally satisfying the needs of shippers. The demand of shippers is usually predicted by a pipeline operator from historical data or obtained from suction during the open season. The commonly applied rules include “first come, first served” and proportional allocation. Considering the various aims of a pipeline company, three allocation rules are proposed in this paper, and three models to calculate commercial capacity are built based on them.

2.2. Peak-shaving capacity

Daily injection and delivery amounts are not always equal because of the fluctuating gas supply and demand, which should be allowed in practice. For example, PipeChina requires that the daily difference between gas input and delivery be less than 3%. Taking advantage of the compressibility of natural gas, the extra injection is stored as a “linepack” and delivered when a delivery exceeds injection.

The minimum period to make an operation plan is a transmission day, which is from 8:00 a.m. one day to the next in China. Thus, the optimization horizon in the peak-shaving capacity calculation in this paper is a transmission day. The peak-shaving capacity of an entry or exit is defined as the maximum extra daily throughput (oversupply or overdelivery), assuming that the throughput at the other boundary nodes is specified. The values of the peak-shaving capacity at each entry/exit are not related; thus, they are expressed as $n_1 + n_2$ values rather than a vector. This type of short-term capacity is heavily influenced by the initial state of a gas network; thus, peak-shaving capacities are calculated with transient models.

There are two purposes of a transient model. First, the peak shaving capacity can be dynamically determined day-ahead with a model based on the current operating state of a gas network. Since the peak-shaving capacity is greatly influenced by various factors, such as the initial state, nominations, and specified entry or exit, the fixed peak-shaving capacity will be quite conservative. A dynamic peak-shaving capacity can make better use of a gas pipeline. Second, if a certain peak-shaving capacity is required in a contract, multiple scenarios should be checked with the selected model to ensure that such a value can always be reached. If the required peak-shaving capacity cannot be satisfied, some commercial capacity should be considered to be spared for peak shaving.

3. Mathematical Model to Calculate the Capacities

The framework of the proposed models is shown in Fig. 1. As described in Section 2.1, capacity vectors are differentially expressed in E/E and P2P regimes, causing some differences in

decision variables, constraints on boundary nodes, and objective vectors. Once a trading regime has been decided and the characteristics of a gas network are described with constraints, the technical capacities can be calculated. Then, considering the demand of shippers, which is predicted or obtained by auction, the commercial capacity is determined. Finally, introducing the initial conditions, the peak-shaving capacity at each entry or exit is calculated with a transient model.

3.1. Constraints

3.1.1. Pipe segments

The steady and transient operations of a gas network are both simulated with partial differential equations (PDEs) for consistent results. Assuming that a pipeline is isothermal and horizontal, the continuity equation, motion equation, and state equation are applied to simulate gas flow. The continuity equation and motion equation are as follows.

$$A \frac{\partial \rho}{\partial t} + \frac{\partial m}{\partial x} = 0 \quad (1)$$

$$\frac{\partial m}{\partial t} + \frac{1}{A} \frac{\partial}{\partial x} \left(\frac{m^2}{\rho} \right) + A \frac{\partial P}{\partial x} + \frac{\lambda m^2}{2dA\rho} = 0 \quad (2)$$

where A is the cross-sectional area of the pipe, m^2 ; ρ is the density of the gas, $\text{kg}\cdot\text{m}^{-3}$; t is the time dimension, s ; m is the mass flow rate of the gas, $\text{kg}\cdot\text{s}^{-1}$; x is the axial dimension, m ; P is the pressure of the gas, Pa ; λ is the coefficient of friction resistance, which can be calculated with Eq. (3); and d is the inner diameter of the pipeline, m . The second item in PDE Eq. (2) is relatively small and can be ignored for a long-distance pipeline.

$$\frac{1}{\sqrt{\lambda}} = -2 \lg \left(\frac{Ke}{3.7d} \right) \quad (3)$$

where Ke is the roughness of the inner wall of the pipe, m .

Partial differential equations are discretized in space and time with the finite difference method since they cannot be directly solved in the optimization model. The partial differential items can be expressed as:

$$\frac{\partial X}{\partial t} = \frac{X_i^{j+1} + X_{i+1}^{j+1} - X_i^j - X_{i+1}^j}{2\Delta t}$$

$$\frac{\partial X}{\partial x} = \frac{X_{i+1}^j + X_{i+1}^{j+1} - X_i^j - X_i^{j+1}}{2\Delta x}$$

$$X = \frac{X_i^j + X_{i+1}^j + X_i^{j+1} + X_{i+1}^{j+1}}{4}$$

where X denotes the parameters of the gas, such as ρ, m, P ; Δt is the time step of the discretized grid, s ; Δx is the space step of the discrete grid, m ; $i \in \{1, \dots, N_x - 1\}$, and N_x is the number of axial nodes of the discretized grid; $N_x = L/\Delta x + 1$, and L is the length of a pipe segment, m ; $j \in \{1, \dots, N_t - 1\}$, and N_t is the number of time nodes of the discretized grid; $N_t = T/\Delta t + 1$, and T is the optimization horizon, s . Then, Eqs. (1) and (2) are transformed into their respective difference Eqs. (4) and (5).

$$A \frac{\rho_i^{j+1} + \rho_{i+1}^{j+1} - \rho_i^j - \rho_{i+1}^j}{2\Delta t} + \frac{m_{i+1}^j + m_{i+1}^{j+1} - m_i^j - m_i^{j+1}}{2\Delta x} = 0 \quad (4)$$

$$\frac{m_{i+1}^{j+1} + m_{i+1}^{j+1} - m_i^j - m_{i+1}^j}{2\Delta t} + A \frac{P_{i+1}^j + P_{i+1}^{j+1} - P_i^j - P_i^{j+1}}{2\Delta x} + \frac{\lambda}{2dA} \left(\frac{m_i^j + m_{i+1}^j + m_i^{j+1} + m_{i+1}^{j+1}}{4} \right)^2 \left(\frac{\rho_i^j + \rho_{i+1}^j + \rho_i^{j+1} + \rho_{i+1}^{j+1}}{4} \right)^{-1} = 0 \quad (5)$$

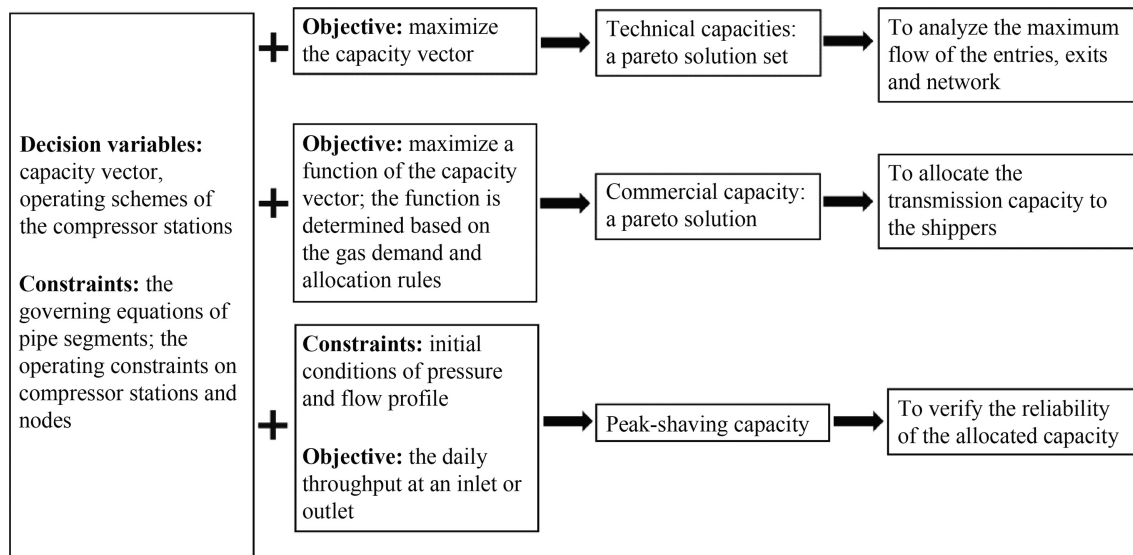


Fig. 1. The framework of the mathematical models used to calculate the technical, commercial, and peak-shaving capacities.

A steady state is considered as a special case of a transient operation, in which the parameters do not change with time, and the partial items in terms of time are equal to zero. This can be modeled by adding constraints Eqs. (6) and (7):

$$\rho_i^{j+1} - \rho_i^j = 0 \quad (6)$$

$$m_i^{j+1} - m_i^j = 0 \quad (7)$$

where $i \in \{1, \dots, N_x\}$ and $j \in \{1, \dots, N_t - 1\}$. It is assumed that $N_t = 2$ to reduce the calculation complexity. The differential forms of Eqs. (4)–(7) are shown in Eqs. (8) and (9), which are the continuity and motion equations, respectively, of gas flow under the steady state.

$$\frac{dm}{dx} = 0 \quad (8)$$

$$A \frac{dP}{dx} + \frac{\lambda m^2}{2dA\rho} = 0 \quad (9)$$

The state equations (BWRS equation) are shown in Eqs. (10) and (11).

$$0.001P_i^j = \rho_{0,i}^j RT + \left(B_0 RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho_{0,i}^{j^2} + \left(bRT - a - \frac{d_0}{T} \right) \rho_{0,i}^{j^3} + \alpha \left(a + \frac{d_0}{T} \right) \rho_{0,i}^{j^6} + \frac{c\rho_{0,i}^{j^3}}{T^2} \left(1 + \gamma \rho_{0,i}^{j^2} \right) \exp \left(-\gamma \rho_{0,i}^{j^2} \right) \quad (10)$$

$$\rho_i^j = \rho_{0,i}^j M_g \quad (11)$$

where $i \in \{1, \dots, N_x\}$; $j \in \{1, \dots, N_t\}$; ρ_0 is the molar density of the natural gas, $\text{kmol} \cdot \text{m}^{-3}$; R is the gas constant, $8.314 \text{ kJ} \cdot \text{kmol}^{-1} \cdot \text{K}^{-1}$; T is the average temperature of the gas, K; M_g is the molar mass of the gas, $\text{kg} \cdot \text{kmol}^{-1}$; and $A_0, B_0, C_0, D_0, E_0, a, b, c, d, \alpha, \gamma$ are determined by gas components. This calculation approach is referred to as Ref. [27].

3.1.2. Compressor stations

There are usually multiple same-type centrifugal compressors working in parallel in a compressor station, with an adjustable

compressor rotational speed. The working state of a single compressor should be within an envelope, as shown in Fig. 2(a). The functional relationship of the flow under the inlet condition and the head under the rated speed can be illustrated as the red curve in Fig. 2(a), while the surge and stonewall flow are located at the left endpoint and right endpoint, respectively. Considering the limit of the speed range of the compressor, the mathematical expression of the working constraints of the compressor can be obtained with the law of similitude. For a station equipped with several centrifugal compressors (for example, three), the number of working compressors can be one, two, or three; thus, the working region is shown in Fig. 2(b).

The relation between inlet flow and the head of a compressor (characteristic curve) under the rated speed n_0 is fitted with a quadratic equation:

$$h_0 = a_0 + a_1 q_1 + a_2 q_1^2 \quad (12)$$

where h_0 is the head of the compressor, m; q_1 is the flow under the inlet condition of the compressor, $\text{m}^3 \cdot \text{s}^{-1}$; and a_0, a_1 , and a_2 are the parameters fitted with the operating data.

The characteristic curve of the compressor under another speed n is obtained based on the law of similitude:

$$h = a_0 \left(\frac{n}{n_0} \right)^2 + a_1 q_1 \left(\frac{n}{n_0} \right) + a_2 q_1^2 \quad (13)$$

where h is the head of the compressor under the speed n , m.

In addition, the surge (minimum) flow $q_{\min}$ and stonewall (maximum) flow $q_{\max}$ under speed n are calculated with Eq. (14) and (15), respectively.

$$q_{\min} = q_{0\min} \times \frac{n}{n_0} \quad (14)$$

$$q_{\max} = q_{0\max} \times \frac{n}{n_0} \quad (15)$$

where $q_{0\min}$ and $q_{0\max}$ are the surge flow and stonewall flow under inlet conditions and the rated speed of the compressor, respectively, $\text{m}^3 \cdot \text{s}^{-1}$.

Binary and integer variables are introduced in the modeling of the compressor station: (1) binary variable Op_i , which denotes the status of compressor station i , where “0” denotes close (bypass) and “1” denotes working; (2) integer variable $N_{c,i}$ ($1 \leq N_{c,i} \leq N_{c,i,\max}$),

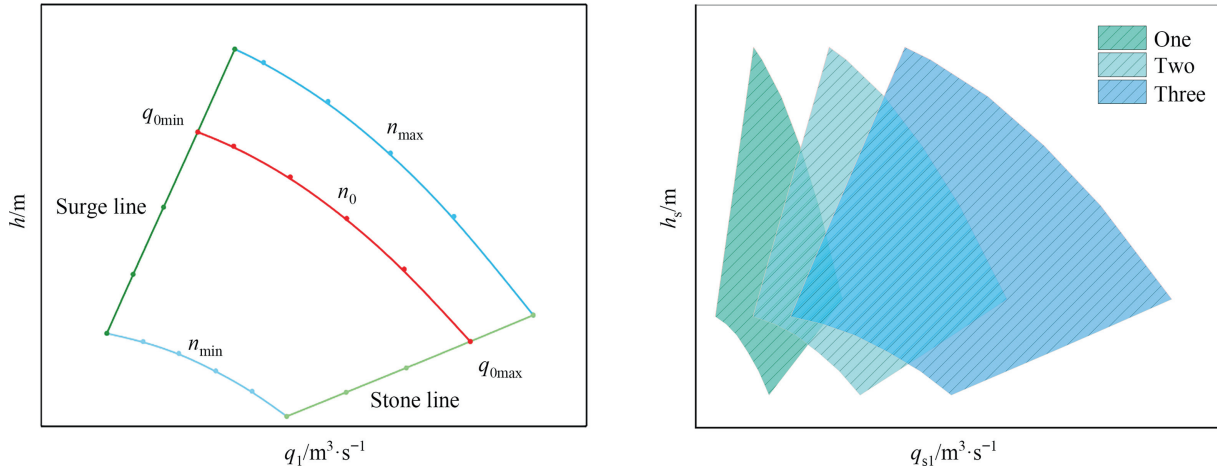


Fig. 2. (a) The operating envelope of a single compressor. (b) The operating region of a compressor station with 3 compressors.

which denotes the number of working compressors in station i . We consider that the status of compressor station Op_i and the number of operating compressors $N_{c,i}$ do not change with time in the transient optimization model because the operating horizon is only 24 h. Therefore, there is no time dimension in the variables Op_i and $N_{c,i}$ in constraint Eqs. (16) and (17).

Therefore, the working constraints of the compressor station are described with constraints Eqs. (16)–(19), which are applied in the mathematical model of the gas network to describe a compressor station. The head of the compressor station is calculated with Eq. (16), where M is a large number. When compressor station i is bypassed ($Op_i = 0$), the head of the compressor station equals to 0; otherwise, the head is calculated with the characteristic function.

$$h_{s,i}^j \leq a_{0,i} \left(\frac{n_i^j}{n_{0,i}} \right)^2 + a_{1,i} \frac{q_{s1,i}^j}{N_{c,i}} \frac{n_i^j}{n_{0,i}} + a_{2,i} \left(\frac{q_{s1,i}^j}{N_{c,i}} \right)^2 + M(1 - Op_i) \quad (16a)$$

$$h_{s,i}^j \geq a_{0,i} \left(\frac{n_i^j}{n_{0,i}} \right)^2 + a_{1,i} \frac{q_{s1,i}^j}{N_{c,i}} \frac{n_i^j}{n_{0,i}} + a_{2,i} \left(\frac{q_{s1,i}^j}{N_{c,i}} \right)^2 - M(1 - Op_i) \quad (16b)$$

$$h_{s,i}^j \geq -MOp_i \quad (16c)$$

$$h_{s,i}^j \leq MOp_i \quad (16d)$$

The inequality constraints Eqs. (17) and (18) limit the working point of the compressor stations within the working envelope. The relation between the outlet pressure and the head of the compressor station is calculated with Eq. (19).

$$N_{c,i}q_{\min,i} \leq q_{s1,i}^j \leq N_{c,i}q_{\max,i} \quad (17)$$

$$n_{\min,i} \leq n_i^j \leq n_{\max,i} \quad (18)$$

$$h_{s,i}^j = \frac{k_v}{k_v - 1} \frac{p_{\text{in},i}^j}{\rho_{\text{in},i}^j g} \left[\left(\frac{p_{\text{out},i}^j}{p_{\text{in},i}^j} \right)^{\frac{k_v-1}{k_v}} - 1 \right] \quad (19)$$

where i is the index of compressor stations; $j \in \{1, \dots, N_t\}$; h_s is the head of the compressor station, m; Q_{s1} is the flow under the inlet condition of the station, $\text{m}^3 \cdot \text{s}^{-1}$; k_v is the volume adiabatic index, $k_v = 1.43$ according to experience; p_{in} , p_{out} are the pressures at the inlet and the outlet of the compressor station, Pa; ρ_{in} is the density

of gas at the inlet of the compressor station, $\text{kg} \cdot \text{m}^{-3}$; and g is the gravitational acceleration, $9.8 \text{ m} \cdot \text{s}^{-2}$.

3.1.3. Nodes

The pressures at the inlets of the initial stations are assumed to be constant. There are always requirements for the minimum delivery pressure in the transmission contracts, ensuring the gas flows downstream. In addition, the operation of compressor stations also requires a minimum inlet pressure for security purposes. Therefore, the lower limits of the pressure at the deliveries and the inlets of the compressor stations are shown in constraint Eq. (20).

$$P_i^j \geq P_{\min,i} \quad (20)$$

where $i \in N_{\text{de}} \cup N_{\text{ins}}$; N_{de} and N_{ins} are the sets of delivery points of the gas network and injection points of compressor stations, respectively; $j \in \{1, \dots, N_t\}$; and $P_{\min,i}$ is the minimum pressure at node i , Pa.

The flows passing the internal nodes of the gas network follow the conservation constraint. The flows at the inlet and outlet of the gas network satisfy Eq. (21) under the E/E model, which satisfies Eqs. (22) and (23) under the P2P model.

$$\sum_j q_i^j = C_i (i \in N_{\text{in}} \cup N_{\text{de}}) \quad (21)$$

$$q_i = \sum_k C_{ik} (i \in N_{\text{in}}, k \in N_{\text{de}}) \quad (22)$$

$$q_k = \sum_i C_{ik} (i \in N_{\text{in}}, k \in N_{\text{de}}) \quad (23)$$

where $j \in \{1, \dots, N_t\}$; N_{in} is the set of the inlets of the gas network; C_i is the capacity at point i , $\text{m}^3 \cdot \text{s}^{-1}$; and C_{ik} is the capacity from node i to node k , $\text{m}^3 \cdot \text{s}^{-1}$.

3.2. Objectives

3.2.1. Technical capacity

The calculation of technical capacities is a multiobjective problem, the objective vector is $\mathbf{C}$. Supposing the feasible region is D , a theorem for the strong Pareto solution is described firstly. There is a map $u: R^n \rightarrow R^1$, and $\mathbf{C}^* \in D$ is the optimal solution of the single-objective optimization model (24). If $u(\mathbf{C})$ is a monotone increasing function, then $\mathbf{C}^*$ is a strong Pareto solution of the original multiobjective problem, which means that no $\mathbf{C} \in D$ satisfies $\mathbf{C} \geq \mathbf{C}^*$, and the technical capacity has reached the maximum.

$$\max_{\mathbf{C} \in D} u(\mathbf{C}_1, \mathbf{C}_2, \dots, \mathbf{C}_n) \quad (24)$$

Based on the above theorem, the multiobjective problem is transformed into multiple single-objective problems, the objective is shown in Eq. (25).

$$\max u(\mathbf{C}) = \omega^T \mathbf{C} \quad (25)$$

where ω satisfies $\sum_{i=1}^n \omega_i = 1, \omega_i > 0, i = 1, \dots, n$. To guarantee that the minimum and maximum of an element in capacity vector are calculated, there are twice the number of elements at least needed for capacity analysis. And the calculated solution set can be larger for a more accurate analysis. Thus, $u(\mathbf{C})$ is a strictly increasing function in terms of $\mathbf{C}$, and the optimal solution $\mathbf{C}^*$ of model (25) is a strong Pareto solution, i.e., the technical capacity of the pipeline network. Infinite technical capacity vectors can be obtained by setting different coefficient vectors, which comprise a strong Pareto solution set.

The mutually restrictive relation between the flows at two injection/delivery points can be analyzed based on the technical capacity set to facilitate adjusting the flow of the network for the operation management personnel. There are four steps after the analyzed points are chosen.

- (1) Filter data. The technical capacities that are selected satisfy that except for the selected injection/delivery points, the weight ω_i of any other injection/delivery point is the minimum.
- (2) The capacity data of the two points to be analyzed only are retained.
- (3) Duplicate data, if identical capacity sets exist, are deleted.
- (4) The capacity sets are reordered so that the flow values of one point increase successively.

The relationship between the capacities at two points can be analyzed by a graph or table based on the data obtained by the above method.

3.2.2. Commercial capacity

The demand of shippers is usually predicted by a pipeline operator from historical data or obtained from auction during the open season. Commercial capacity is one of the technical capacities allocated based on demand. Suppose that the demand is obtained as a vector $\mathbf{d} = (d_1, d_2, \dots, d_n)$. The variable d_i denotes the total demand for capacity of all shippers at point i in the E/E regime, where $n = n_1 + n_2$. However, d_i denotes the total capacity demand of route i from an entry to an exit in the P2P regime, where $n = n_1 \times n_2$. A pipeline company cannot determine whether the demand can be satisfied, or how to allocate the capacity when shippers cannot be fully satisfied, on the basis of technical capacity vectors directly in most cases. The commercial capacity allocation model is supposed to solve the above problems.

First, supposing the demand of shippers cannot be fully satisfied at the same time, which is called “contractual congestion”, the pipeline company can accept, adjust or reject some applications. However, the rules should be reasonable and transparent to determine a feasible commercial capacity allocation for the shippers.

The common rules for allocation include first-come, first-served, and served by proportion; in addition, a pipeline company can design an allocation method according to its aims, such as the benefit, supply security, or utilization of the transmission capacity, etc. There are three rules set as the objectives of an allocation model to find the commercial capacity in this paper. In addition, it is proven that the allocated capacity is one of the technical capacities under these three rules, i.e., the transmission capacity of the pipeline has been made the most. The rules and corresponding objective functions are as follows.

- (1) The total difference between each contracted capacity and the corresponding demand is minimized. This can be considered a goal programming model transformed from the original multiobjective model. The objective is minimizing the 1-norm of the difference between the commercial capacity vector and demand vector $\mathbf{d}$, as shown in Eq. (26).

$$\min \|\mathbf{C} - \mathbf{d}\|_1 \quad (26)$$

The above objective is nonlinear, which can be transformed to a linear objective as shown in Eq. (27). The objective has been proved to obtain a strong Pareto solution.

$$\min \sum_{i=1}^n (\delta_i^+ + \delta_i^-) \quad (27)$$

$$\text{s.t. } C_i - \delta_i^+ + \delta_i^- = d_i, \delta_i^+, \delta_i^- \geq 0 \quad (i = 1, \dots, n)$$

where δ_i^+ and δ_i^- are the positive bias and negative bias between C_i and d_i , respectively.

- (2) The capacity is allocated by proportion φ and φ is maximized. This objective is shown as Eq. (28).

$$\max \varphi \quad (28)$$

$$\text{s.t. } \mathbf{C} = \varphi \mathbf{d}$$

However, this objective cannot guarantee that the solution is a strong Pareto solution of the original multiobjective model. When a component C_i has reached its maximum ($C_i^* = \varphi^* d_i$), other components C_j always equal $\varphi^* d_j$, even if the residual capacity can be used at j , which means that function $\varphi|\mathbf{C} = \varphi \mathbf{d}$ is not strictly monotonically increasing in terms of $\mathbf{C}$. Thus, to ensure that the commercial capacity is one of the technical capacities, objective Eq. (29) is applied instead.

$$\max \alpha + \varepsilon \sum_{i=1}^n \varphi_i \quad (29)$$

$$\text{s.t. } C_i = \varphi_i d_i \quad (i = 1, \dots, n)$$

$$\alpha \leq \varphi_i \quad (i = 1, \dots, n)$$

where ε equals a relatively small value, such as 0.1, and α equals the minimum proportion. The objective function can be expressed as $u = \min_i (C_i/d_i) + \varepsilon \sum_i C_i/d_i$, which is strictly monotonically increasing in terms of $\mathbf{C}$. In such a model, the minimum proportion is maximized while maximizing the satisfaction of all the other users.

- (3) The income of capacity trading is maximized. The unit prices form a vector $\mathbf{C}$, the dimension of which equals the commercial capacity in the corresponding E/E or P2P regime. The objective is shown in Eq. (30), which is strictly monotonically increasing in terms of $\mathbf{C}$ and leads to a strong Pareto solution of the original multiobjective model.

$$\max \sum_{i=1}^n c_i C_{1,i} + \varepsilon_i (C_i - C_{1,i}) \quad (30)$$

$$\text{s.t. } C_{1,i} \leq d_i \quad (i = 1, \dots, n)$$

where ε_i is a relatively small value; and $C_{1,i}$ is a part of the allocated capacity that is below d_i . We consider that there is minimal revenue when the capacity C_i exceeds the demand d_i .

Note that if the demand can be satisfied in the network, $\mathbf{C}^*$ will be no less than $\mathbf{d}$ from a componential viewpoint in the above three

models, which means that the models can also determine if the demand is feasible.

3.2.3. Peak-shaving capacity

Supposing the initial status (pressure and flow profiles) of a gas network has been obtained from data acquisition or simulation, the maximum oversupply quantity at each entry or overdelivery quantity at each exit in the following transmission day is calculated with the transient optimization model. The optimization horizontal is 24 h. The variable C_i^p is the oversupply/delivery capacity at the entry (exit) i , assuming that the throughputs at other points are equal to the nominations. The objective is shown in Eq. (31).

$$\text{Max } C_i^p \quad (31)$$

$$\text{s.t. } C_i = \text{Nom}_i + C_i^p$$

$$C_j = \text{Nom}_j$$

where $i \in N_{\text{de}} \cup N_{\text{in}}$; $j \neq i, j \in N_{\text{de}} \cup N_{\text{in}}$; $k \in \{1, \dots, N_k\}$; Nom_i is the nomination submitted by shippers at an entry/exit i .

3.3. Formulations

3.3.1. Technical and commercial capacity

The decision variables in technical capacity and commercial capacity calculation include: (1) the capacity vector $\mathbf{C}$, which is expressed as $\mathbf{C}_{n_1+n_2}$ in the E/E regime, while expressed as $\mathbf{C}_{n_1 \times n_2}$ in the P2P regime; (2) the status of compressor stations (Op_i), the number of operating compressors in each station ($N_{c,i}$), and their rotational speed (n_i).

The objective of the technical capacity is the weighted sum of the capacity vector, as shown in Eq. (25). The objective of the commercial capacity depends on the aim of the pipeline company, which can be shown in Eqs. (27), (29), or (30).

The constraints are:

- (1) The flow equations of the gas in pipe segments as Eqs. (3)–(7) and the gas state equations as Eqs. (10) and (11);
- (2) The equation for calculating the head of a compressor station as Eq. (16); the flow limit of a compressor station as Eq. (17); the rotational speed limit of a compressor as Eq. (18); the relationship between outlet pressure and the head of a compressor station as Eq. (19).
- (3) The constant pressures at the inlet of initial stations;
- (4) The lower limit of the pressure at deliveries or inlets of compressor stations as Eq. (20);
- (5) The flow conservation equations, which are Eq. (21) under the E/E model and Eqs. (22) and (23) under the P2P model.

3.3.2. Peak-shaving capacity

The decision variables in the peak-shaving capacity analysis include: (1) over-supply or over-delivery capacity C_i^p at a specified node i ; (2) the status of compressor station i (Op_i); (3) the number of operating compressors in station i ($N_{c,i}$); (4) rotational speed of compressors at station i at time j (n_i^j).

The objective is to maximize the over-supply or over-delivery capacity C_i^p at a specified node i as shown in Eq. (31).

The constraints are:

- (1) The initial pressure and flow rate profiles;
- (2) The flow equations of the gas in pipe segments as Eqs. (3)–(5) and the state equations of the gas as Eqs. (10) and (11);
- (3) The constraints on compressor stations as Eqs. (16)–(19);
- (4) The constant pressures at the inlet of the initial stations;

(5) The lower limit of the pressure at deliveries or inlets of compressor stations as Eq. (20);

(6) The flow conservation equations as Eq. (21).

3.4. Solution

To find the technical and commercial capacity, large MINLP models are built. The scales of the models depend on the actual network and step size of the discretization. The scales and the calculation time are given in the following case study. Note that the number of integer variables is twice the number of compressor stations, so the number of continuous variables is much greater than that of the integers. A solution is found with an NLP-based branch and bound method. Optimizers named “Juniper” [28] and “Ipopt” [29] are applied to solve the problem. Juniper addresses the integer variables with the branch and bound method. There is an interface in Juniper to call a solver to solve the nonlinear and nonconvex subproblems. In this paper, the subproblems are solved with “Ipopt” using the interior point method, which finds a local optimum with high efficiency.

The optimization model for peak-shaving capacity is also nonlinear and involves integer variables. In addition, the number of variables and constraints almost increases with the number of time steps linearly. Considering nonlinear, integer variables and multiple time steps at the same time will be time-consuming, the original problem is solved in two stages, integer and continuous variables are optimized respectively:

- (1) The optimal solution of binary variables Op_i and integer variable $N_{c,i}$ based on a long time step is found. In this stage, an MINLP model Eq. (31) is optimized with Juniper and Ipopt.
- (2) The optimal values of continuous variables with a relatively short time step based on the solution of integer variables optimized in the first stage are calculated. Therefore, model Eq. (31) is simplified into an NLP model and solved with Ipopt, allowing more time steps to make the calculation more accurate.

4. Case Study

4.1. Physical structure

A network simplified from a real network is applied to demonstrate the ability of the method, whose topology is shown in Fig. 3. There are two inlets, four outlets, and six compressor stations in the network. The pipe denoted with dotted line can be cut off by the operators. The detailed characteristics of the compressor stations and pipe segments are listed in Tables 1 and 2, respectively.

4.2. Technical capacity

The objective vector is $\mathbf{C} = (C_1, C_2, \dots, C_6)$ in the E/E regime, where C_1, C_2 are the injection capacities at S1 and S2, respectively, and C_3 – C_6 are the delivery capacities at D1–D4. A series of strong Pareto solutions are obtained by model (25) with the weighing coefficients satisfying Eq. (32).

$$\begin{aligned} \omega_1 + \omega_2 &= 0.5 \\ \omega_3 + \omega_4 + \omega_5 + \omega_6 &= 0.5 \\ \omega_1, \dots, \omega_6 &> 0 \end{aligned} \quad (32)$$

The value of ω can be obtained by random sampling. However, to ensure that the solutions are distributed uniformly in this work, the possible values of ω_1 or ω_2 are 0.01, 0.25, and 0.49, and the possible values of ω_3 – ω_6 are 0.01, 0.24, and 0.47. Therefore, 30

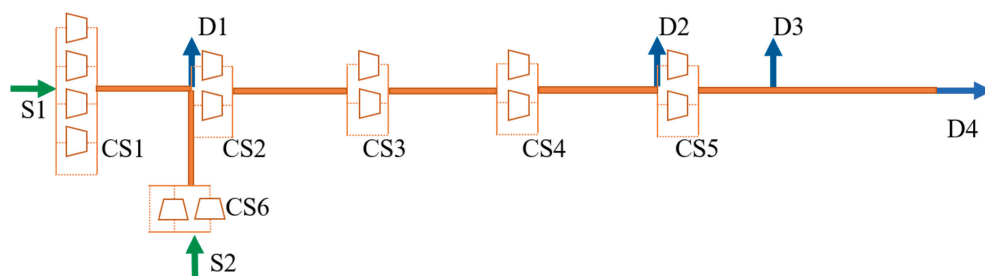


Fig. 3. The topology of the network.

Table 1

Characteristics of the compressor stations

Compressor station	Number of working compressors	The characteristic function of a single compressor at the rated speed	Minimum, rated and maximum rotational speed of the compressor/r.min ⁻¹	Minimum and maximum flow of the compressor at rated speed/m ³ .s ⁻¹
CS1	4	$h = -1423.7q_1^2 + 4713.0q_1 + 6635.9$	6000/8000/10500	1.7962/3.6336
CS2	2	$h = -243.4q_1^2 + 684.2q_1 + 8677.2$	5120/9030/9030	2.9113/6.3333
CS3	2			
CS4	2			
CS5	2			
CS6	2	$h = -322.1q_1^2 + 1423.0q_1 + 11743.0$	3120/4800/5040	2.8525/6.3139

Table 2

Characteristics of the pipe segments

	Length/km	Wall thickness/mm	External diameter/mm	Roughness/mm	Designed pressure/MPa
Line S1–D4	CS1–CS2	170	1016	0.017	10
	CS2–CS3	170			
	CS3–CS4	170			
	CS4–CS5	170			
	CS5–D3	110			
	D3–D4	120			
Line S2–D1	190	17	1016	0.017	10

sets of weighting coefficients and technical capacities are obtained. The values of ω and C^* are shown in Tables S1 and S2 (in Supplementary Material), respectively.

Each row in Table S2 is one of the technical capacities of the gas network. The flow cannot increase at any entry/exit without reducing the flow at other entries/exits. Taking the first and third technical capacities as examples, $C^1 = (36.83, 52.81, 43.86, 0, 0, 45.77, 89.64)$ and $C^3 = (44.82, 36.59, 34.54, 1.09, 0, 45.77, 81.40)$. Although the total throughput of the gas network in case 1 is larger than that in case 3, the flows at different entries or exits are not equivalent, which means that the value of vectors C^1 and C^3 are incomparable, and they are both technical capacities of the gas network. The intervals of daily throughputs at the entries and exits when the gas network reaches technical capacities are summarized in Table 3 based on Table S2.

Table 3

The flow intervals of capacities at the injection and delivery points

Capacity	Interval $\times 10^{-6} / \text{m}^3 \cdot \text{d}^{-1}$	Capacity	Interval $\times 10^{-6} / \text{m}^3 \cdot \text{d}^{-1}$
C_1	[36.72, 44.82]	C_4	[0, 52.57]
C_2	[36.59, 53.05]	C_5	[0, 52.57]
C_3	[28.83, 80.31]	C_6	[0, 45.77]
Total throughput	[81.40, 89.93]		

By comparing Table 3 with the actual flow data, one can preliminarily determine whether the current operation status of the pipeline network has reached the transmission capacity. If the current flow at a point is less than the minimum value of the corresponding interval, it is considered that the point has not reached the technical capacity; if the current flow of a point is equal to the maximum value of the interval, the flow of the point could not increase in any way; if the current capacity of a point is within the range of the interval, the capacity of the entry (exit) may not be adjusted independently, depending on the flow of other entries (exits). The model contains 555 variables and 527 constraints. The computational time of a single solution is between 2.7 and 108.1 s, and the total computational time for 30 solutions is 923 s (CPU: AMD Ryzen 7 5800H, 3.20 GHz; RAM: 16.0 GB).

The mutually restrictive relation between the flows at S1 and S2 is analyzed. The curves of C_1 , C_2 , and their sum are shown in Fig. 4 when the gas network reaches its technical capacity. When the value of C_1 ranges in [36.72, 36.88], the values of C_1 and C_2 are not mutually restrictive. However, the flows at the two points are mutually restrictive when C_1 is in the range of [36.88, 44.82], which indicates that C_2 needs to be decreased to increase C_1 in this interval.

The capacities of routes between each entry and exit are considered in the P2P regime. The objective vector is $C = (C_1, C_2, \dots, C_8)$, where C_1 – C_4 are the capacities from S1 to D1–D4, respectively, and C_5 – C_8 are the capacities from S2 to D1–D4. The Pareto solutions are calculated by model (25) with the weighting coefficients

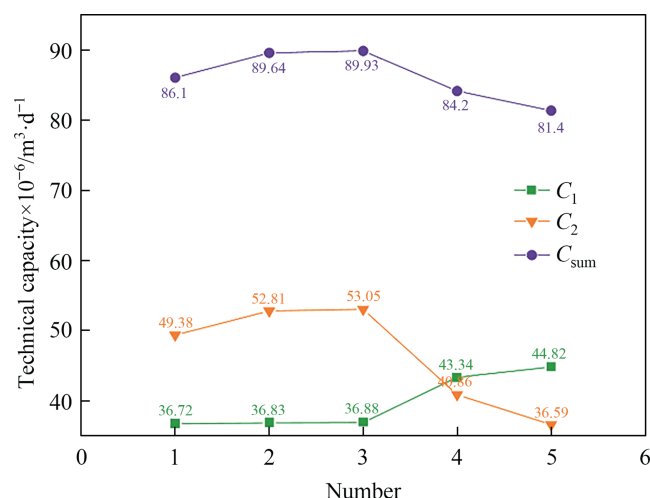
Fig. 4. Curves of C_1 , C_2 , and $C_1 + C_2$.

Table 4

The intervals of the capacities of the routes between injection and delivery points

Capacity	Interval $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$	Capacity	Interval $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$
C_1	[0, 44.82]	C_5	[0, 53.05]
C_2	[0, 44.34]	C_6	[0, 50.50]
C_3	[0, 44.82]	C_7	[0, 50.50]
C_4	[0, 44.82]	C_8	[0, 45.77]
Total throughput	[81.40, 89.93]		

satisfying Eq. (33). The possible values of ω_i are 0.02, 0.44, and 0.86. There are 36 sets of weighting coefficients and solutions generated and shown in Tables S3 and S4, respectively.

Table 5

Allocation of the commercial capacity in the E/E regime

	Demand $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 1	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 2	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 3
S1	42	36.66/0.873	37.38/0.890	36.71/0.897
S2	53	51.63/0.974	47.17/0.890	49.40/0.932
D1	40	40.00/1.000	35.60/0.890	33.68/0.842
D2	5	5.00/1.000	4.45/0.890	3.65/0.730
D3	5	5.00/1.000	4.45/0.890	5.00/1.000
D4	45	38.29/0.851	40.05/0.890	43.78/0.973
Total supply	95	88.29/0.929	84.54/0.890	86.12/0.906

Table 6

Allocation of the commercial capacity in the P2P regime

	Demand $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 1	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 2	Quantity $\times 10^{-6}/\text{m}^3 \cdot \text{d}^{-1}$ or satisfaction degree under Rule 3
S1–D1	40	36.62/0.915	35.60/0.890	34.67/0.867
S1–D2	2	0/0	1.78/0.890	2.00/1.000
S1–D3	0	0	0	0
S1–D4	0	0	0	0
S2–D1	0	0	0	0
S2–D2	3	3.00/1.000	2.67/0.890	0.99/0.328
S2–D3	5	5.00/1.000	4.45/0.890	5.00/1.000
S2–D4	45	42.48/0.944	40.05/0.890	43.78/0.973
Total supply	95	87.09/0.917	84.54/0.890	86.44/0.910

$$\sum_{i=1}^{\infty} \omega_i = 1 \quad (33)$$

$$\omega_1, \dots, \omega_8 > 0$$

The model contains 547 variables and 527 constraints. The time for calculating a single solution varies from 0.77 to 30.9 s, and the total time is 376.7 s. The intervals of the capacities of the routes are shown in Table 4.

The flow intervals of each route of the gas network, when the status of the gas network reaches the technical capacity, are shown in Table 4. The analysis of the restrictive relation of two components in the capacity vector in the P2P regime is similar to that in the E/E regime. However, there are more objects to be analyzed in the P2P regime, making the analysis more complex.

Note that the range of the total throughput of the gas network when the technical capacity is reached in the P2P regime equals that in the E/E regime, showing that the range of the total throughput only depends on the gas network characteristics rather than the tariff regime.

4.3. Commercial capacity

The three commercial capacity allocation rules proposed in Section 3.3.2 are applied in a case study. Assume that the demand is summarized in a vector $\mathbf{d}$ (unit: $10^6 \text{ m}^3 \cdot \text{d}^{-1}$) = (42, 53, 40, 5, 5, 45) based on a prediction or an auction in the E/E regime, and the tariff vector $\mathbf{c}$ (unit: $\text{USD} \cdot \text{m}^{-3}$) = (0.115, 0.119, 0.036, 0.138, 0.160, 0.184). The results are compared in Table 5.

The demand of shippers is $\mathbf{d} = (40, 2, 0, 0, 0, 3, 5, 45)$ in the P2P regime. Assuming the unit price $\mathbf{c}_0 = 4 \times 10^{-4} \text{ USD} \cdot \text{m}^{-3} \cdot \text{km}^{-1}$, then vector $\mathbf{c}$ (unit: $\text{USD} \cdot \text{m}^{-3}$) = (0.068, 0.272, 0.316, 0.364, 0.076, 0.280, 0.324, 0.372). The results are shown in Table 6.

The total throughput of the network under Rule 1 is the maximum of three, but the allocation under Rule 3 is the most profitable for the pipeline company. However, Rule 3 implies discrimination against short-distance transmission contracts, which does not meet the principle “fair, nondiscriminatory”

required by regulatory authorities in transmission capacity allocation, while Rule 2 conforms more to this principle. In addition, pipeline companies may comprehensively consider the total throughput, user satisfaction, income, and other factors and propose a multiobjective optimization scheme to allocate the commercial capacity of the gas network.

4.4. Peak-shaving capacity

Peak-shaving capacity is calculated by the transient optimization model, in which the initial state of the operation should be known in advance. The initial state is obtained from a steady-state simulation in this case study. Suppose that the current flow vector is (37.4, 47.2, 35.7, 4.4, 4.5, 40.0). There are two scenarios compared: high and low initial operating pressures, which are listed in Table 7.

In this case, $\Delta t = 6 \times 3600$ s and $N_t = 5$ in the first stage of the optimization model. There are six models to be solved, each model contains about 1900 variables and 1600 constraints, and the computational time varies from 156 to 1549 s. As a result, $Op = (1, 1, 1, 1, 1, 1)$, $N_c = (4, 2, 3, 3, 2, 3)$. In the second stage, $\Delta t = 3600$ s, and $N_t = 25$; each model contains about 6600 variables and 6300 constraints, and the computational time varies from 17 to 132 s. The maximum oversupply and overdelivery flows at each entry or exit in the next transmission day are calculated and shown in Table 8, supposing that the throughputs at the other points are specified. The ratio of the oversupply or overdelivery throughput to the total steady throughput is also contained in the table.

Supposing that the peak shaving capacity is required to be larger than 3% of the nomination, it can be satisfied when the pipeline is operated at low pressure but not at high pressure. Hence, the peak shaving capacity should be considered when the operating scheme is determined. Normally, a higher initial operating pressure of the network means more lineup, larger overdelivery throughput provided to the user, and smaller oversupply, and vice versa. Pipeline companies should pay more attention to the impact of operating pressure on the reliability of gas transmission, maintaining a high operating pressure during periods of large fluctuations in gas consumption and low pressure during periods of large fluctuations in supply.

Table 7
The different operating pressure schemes of the compressor stations

Compressor station	Flow rate $\times 10^{-6}/\text{m}^3\cdot\text{d}^{-1}$	Scenario 1: high initial pressure/kPa	Scenario 2: low initial pressure/kPa
CS1	37.4	8764	8218
CS2	48.9	10000	9334
CS3	48.9	10000	9322
CS4	48.9	10000	9312
CS5	44.5	10000	9548
CS6	47.2	10000	9526

Table 8
The peak shaving capacity of the network

	Oversupply or overdelivery capacity at each entry or exit $\times 10^{-6}/\text{m}^3\cdot\text{d}^{-1}$					
	S1	S2	D1	D2	D3	D4
High pressure	1.541 <u>1.9%</u>	0 <u>0%</u>	17.172 <u>21.5%</u>	8.217 <u>10.3%</u>	7.400 <u>9.3%</u>	4.136 <u>5.2%</u>
Low pressure	7.304 <u>9.1%</u>	5.191 <u>6.5%</u>	11.360 <u>14.2%</u>	6.400 <u>8%</u>	7.386 <u>9.2%</u>	4.226 <u>5.3%</u>

The scenario in which the nomination is equal to the commercial capacity should be verified since it is considered to be the toughest scenario. In this case study, the commercial capacity is verified to show that the pipeline system can satisfy the required peak-shaving capacity. If such a scenario cannot be satisfied, the commercial capacity should be considered to be reduced.

5. Conclusions and Future Work

A gas pipeline network research system is proposed in this paper, i.e., concepts and calculation methods to determine technical capacity, commercial capacity, and peak-shaving capacity. The conclusions are as follows.

- (1) The technical capacities of the pipeline network consist of a Pareto solution set, which can fully reflect the effect of flow distribution at routes or entries and exits on gas transmission capacity.
- (2) The commercial capacity is one of the technical capacities, to make sure that the pipeline system is fully utilized.
- (3) The reliability of pipeline transmission can be improved by verifying the peak shaving capacity under various operating conditions before the allocation of the commercial capacity. Calculating the peak-shaving capacity dynamically with the proposed model can improve the utilization of a pipeline network.

The modelling method proposed in this paper can be referred to build a larger scale gas network, but a preprocessing of the model is expected before solving, since it is hard to find a solution of the larger scale MINLP model directly with existing solvers. In addition, the reliability of the commercial capacity should be evaluated considering the uncertainty of the nominations in the future, since the nominations of shippers in this model are assumed to be equal to the contracted maximum nominations in this paper.

Data Availability

Data will be made available on request.

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.

Supplementary Material

Supplementary material to this article can be found online at <https://doi.org/10.1016/j.cjche.2022.12.010>.

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