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Processing capacity allocation of multiple production system for gas field multi-stage development

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A B S T R A C T

The multi-stage development strategy is often adopted in the gas field. However, when the productivity decline occurs, many large processing stations will be severely idle and underutilized, significantly reducing operating efficiency and revenue. This study proposes a novel operation mode of multiple gathering production systems for gas field multi-stage development, integrating the decisions about processing capacity allocation and infrastructure construction to share processing stations and improve multi-system operating efficiency. A multi-period mixed integer linear programming model for multi-system operation optimization is established to optimize the net present value (NPV), considering the production of gas wells, time-varying gas prices, and the capacity of processing stations. The decision of processing capacity, location, construction timing, and capacity expansion of processing stations, as well as transmission capacity of pipelines and processing capacity allocation schemes, can be obtained to meet long-term production demand. Furthermore, a real case study indicates that the proposed processing capacity allocation approach not only has a shorter payback period and increases NPV by 4.8%, but also increases the utilization efficiency of processing stations from 27.37% to 48.94%. This work demonstrates that the synergy between the processing capacity allocation and infrastructure construction can hedge against production fluctuations and increase potential profits.

1. Introduction

The multi-stage development strategy (Wang et al., 2018a; He et al., 2019) in the gas field is often adopted, which gives priority to the development of high-reserve blocks, and then gradually develops other blocks to supplement and expand gas field production (Wang et al., 2019; Hong et al., 2020a). Each block has its gathering production system comprising well sites, pipelines, and processing stations (Hong et al., 2019; Xue et al., 2024). All raw natural gas produced by the gas well sites before entering the downstream gas market is gathered and transported to the processing stations (Zhou et al., 2019). However, when the productivity decline occurs, many large processing stations will be severely idle and underutilized, significantly reducing operating efficiency and revenue (Gao and You, 2017a; Hong et al., 2020b). Therefore, it is necessary to increase production flexibility to cope with the risks posed by fluctuations in natural gas production (Tan and Barton, 2016). This work mainly focuses on the operation optimization of multiple gathering production systems for multi-stage development of natural gas and realizes production flexibility sharing through processing capacity allocation.

In recent years, many studies have combined operations research and process systems engineering methods to achieve economic efficiency, environmental sustainability, and social responsibility for the natural gas gathering production system. These studies include strategic planning and operation optimization of

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natural gas gathering production systems. Strategic planning, usually involves the construction of infrastructure (Cafaro and Grossmann, 2014; Arredondo-Ramírez et al., 2016), the selection of technologies and contracts (Drouven and Grossmann, 2016), and the design of the natural gas supply chain (Gao and You, 2015a, 2017b). However, most studies aim at a single gathering production system, which is not suitable for multiple gathering production systems in the process of natural gas multi-stage development. With the attention to environmental safety, more scholars consider the environmental factors in natural gas production systems through the life cycle assessment (Chen et al., 2017; Gao and You, 2018) and dynamic material flow analysis (Gao and You, 2015a). Nevertheless, these studies are mainly to design and optimize the supply chain from a more macro perspective, and the characteristics of gathering production systems are not minutely described.

Operation optimization is related to drilling activity allocation (Wilson and Durlofsky, 2013; Drouven et al., 2017), natural gas production (Ondeck et al., 2019a), and water management (Gao and You, 2015b; Guerra et al., 2016, 2019). Redutskiy et al. (Redutskiy, 2017) introduced a multi-period MINLP model, which can simultaneously determine the layout of infrastructure, the pressure and flow in the gathering production system, and the performance of artificial lift. It can eventually coordinate the gas field development and production operations in the entire life cycle. Ondeck et al. (2019a) focused on the development of natural gas pads with a fixed sequence of development operations and presented a modeling framework to obtain the economical allocation of well development operations and natural gas production. Since the exploitation of natural gas fields relies on hydraulic fracturing, the optimization of water management should be carefully integrated during natural gas production (Guerra et al., 2019).

However, existing studies mostly focus on single-gathering production systems with only one central processing station, and the construction cost of the processing station is ignored or taken as a fixed value. A few studies (Hong et al., 2018; Wang et al., 2018a) consider multiple gathering production systems but fail to obtain better economic benefits owing to the inconsideration of the influence of station processing capacity and equipment utilization rate. More specifically, most of these studies assume that the processing station has sufficient processing capacity, ignoring its impact on operation costs. In fact, as core components of the gathering production system, processing stations have higher construction investment and operation costs compared with pipelines (Zhang et al., 2017; Wang et al., 2018a, 2018b), and their utilization directly affects operating efficiency and economic benefits (Liu et al., 2015; He et al., 2019; Hong et al., 2019, 2020a). In summary, most of the current studies ignore the utilization efficiency of processing stations, which makes it difficult to improve the production flexibility to adapt to the fluctuations caused by the rapid decline in natural gas production.

This study aims to propose an operation mode of multi-production systems for natural gas multi-stage development and the corresponding optimization method to improve production flexibility. To the best of our knowledge, there is no such work that integrates the capacity and equipment utilization rate of processing stations with multi-system operation optimization. The novel contributions of this study can be summarized as follows.

(i) A new operation mode based on processing capacity allocation via interconnected pipelines is proposed to share processing stations which can improve production flexibility and operating efficiency of multi-production systems.
(ii) A mixed integer linear programming (MILP) operation optimization model for the design and operation of natural gas multi-system is proposed to maximize the NPV of profits, considering the selection of processing capacity, location, construction timing, and capacity expansion of processing stations, the transmission capacity of pipelines as well as processing capacity allocation to meet long-term production demand.
(iii) The advantages of the processing capacity allocation approach over the conventional method are illustrated through a case study. In addition, the impact of natural gas production and price is identified by sensitivity analysis.

The rest of this paper is organized as follows. First, Section 2 presents a detailed description of the optimization problem and proposes a novel operation mode based on processing capacity allocation. Meanwhile, the required parameters, decision variables, and basic assumptions are also stated. Then, the MILP model is established in Section 3, followed by a case study to illustrate the feasibility and advantages of the proposed model in Section 4. Finally, Section 5 summarizes this study and looks forward to future work.

2. Problem statement

As mentioned above, the multi-stage development strategy is usually adopted (Wang et al., 2018a; He et al., 2019). However, in the multi-stage development process, the sharing of processing capacity cannot be realized and conflicts often arise because the interconnection between the various blocks of gas sources is not implemented. On the one hand, when the output of the developed block decreases in the later stage of production, the processing capacity of the original processing station is idle, resulting in low utilization. On the other hand, the raw natural gas produced in the new blocks has to be processed by processing equipment, but at this time, if there is no processing station in the new block, the raw gas only can be discharged into the air or be combusted, which will not produce benefits but also pollute the atmospheric environment. However, if a new processing station is built on the new block, the processing equipment remains idle until it enters a stable production stage. Therefore, the multi-stage development of natural gas fields often suffers from large energy consumption, massive investment, and a high rate of idle.

To solve this problem, this paper proposes a new operation mode based on processing capacity allocation via interconnected pipelines as shown in Fig. 1. In this example, there are four natural gas source blocks, two of which are producing and two are prospective. Since there is an interconnected pipeline between #1 and #2 blocks, so if #1 block has sufficient processing capacity, the raw natural gas produced in #2 block can be directly transported to #1 block for processing; if the processing capacity of #1 block is insufficient, the processing station of #1 block can be expanded first, and then the raw natural gas produced in #2 block can be directly transported to #1 block for processing. Therefore, it is unnecessary to establish an additional processing station in the #2 block. Similarly, the expected #3 and #4 gathering production systems have the option of establishing their processing stations or interconnected pipelines to transport raw natural gas to other blocks for processing. By adopting such an allocation scheme in the proposed new operation mode, the processing equipment is shared among multiple gathering production systems between different gas source blocks, to reallocate the idle processing capacity of the old block to other new blocks under development.

Different processing capacity allocation schemes affect the utilization, construction, and operation costs of processing stations.

This study proposes an operation mode of multi-production systems based on processing capacity allocation and the corresponding optimization method, maximizing the profitability and flexibility of natural gas field production over the entire time horizon. There are some assumptions as follows.

(1) Gas reservoir engineers formulate a production plan for each well site, and the productivity of each gas well in each period is a fixed value (Allen et al., 2019; Hong et al., 2020b).
(2) The processing station of each block can be expanded to increase the corresponding processing capacity, but it can only be expanded once. There is only one connected pipeline between two blocks. Once the pipeline type is determined, it cannot be changed or expanded (Tan and Barton, 2015, 2016).
(3) The planning time range can be divided into a set of discrete periods (Tan and Barton, 2016; Drouven and Grossmann, 2017; Ondeck et al., 2019b). The time required for pipeline construction, processing station construction, or expansion is an integral multiple of the unit time.
(4) The focus of this work is to investigate the optimization of processing capacity allocation among multiple gathering production systems. Therefore, it is assumed that the gathering pipeline network inside each gathering production system has been constructed.
(5) The construction and expansion of compressor stations is not considered, assuming that gas Wells and pipelines have sufficient pressure to transport shale gas.

Given.

(1) Natural gas parameters: the location and production plan over each period of natural gas wells, terrain obstacles for building pipelines, and gas prices for qualified pipeline gas in different periods.
(2) Construction parameters: the location, type, and available status of pipelines and processing stations in the initial period.
(3) Equipment parameters: the lead time, construction cost, operation cost, and maximum processing capacity of different types of processing stations, the lead time, maximum delivery capacity, and construction cost of different diameter pipelines.

Determine.

(1) The construction plan (time, location, type) of processing stations and interconnected pipelines.
(2) Processing capacity allocation schemes: the time, direction, and quantity at each period.
(3) Economic results: the cash flow in different periods (the sales revenue of qualified pipeline natural gas, the construction and operation costs of each block), the NPV of the gas field production.

3. Optimization model

Based on the above assumptions, natural gas parameters, construction parameters and economic parameters, a multi-period MILP model for multi-system operation optimization for shale gas field multi-stage development is established to obtain the construction plan, processing capacity allocation schemes and economic results. The proposed model based on flowrate allocation mainly considers the construction, expansion and capacity of processing stations as well as the construction of pipelines, maximizing the *NPV* of the profit. The maximum NPV of profit is taken as an objective function, where r is an appropriate discount rate:

$$\mathrm{NPV} = \sum_{t\in T}\frac{\mathrm{CF}_t}{(1+r)^{t-1}} \tag{1}$$

The cash flow (CF_t) contains six parts, namely, the revenue of the sales of qualified pipeline gas (Rev_t), the construction cost of pipelines (C_t^p) and processing stations (C_t^{ps}), the construction cost of expanding processing stations (Ce_t^{ps}), the total operation cost of processing stations (Ct_t^{ope}) and the flowrate allocation cost between different gas sources (C_t^{fl}).

$$\mathrm{CF}_t = Rev_t - C_t^{p} - C_t^{ps} - Ce_t^{ps} - Ct_t^{ope} - C_t^{fl} \quad \forall t\in T \tag{2}$$

(1) Economic cost constraints (3–9)
(2) Interconnected pipeline construction constraints (10–20)
(3) Processing station construction constraints (21–29)
(4) Processing station expansion constraints (30–37)
(5) Processing stations capacity constraints (38–42)
(6) Flowrate allocation constraints (43–51)

3.1. Economic cost constraints

The qualified pipeline gas revenue for each time period (Rev_t) is the product of the shale gas price (p_t) and the total qualified production of the gas field ($Q_{b,t}^{pro}$). The number of working days in period t is represented by σ_t. μ is the conversion coefficient, which represents the efficiency of converting wellhead raw shale gas into qualified pipeline gas.

$$Rev_t = \sigma_t\cdot\mu\sum_{i\in I}Q_{b,t}^{pro}\cdot p_t \quad \forall t\in T \tag{3}$$

The cost of pipeline construction (C_t^p) is the unit price (c_p^p) multiplied by the distance of the pipeline ($dis_{b,b'}$), and the unit price (c_p^p) is determined by the diameter. $Bc_{b,p,t,b'}^p$ is the binary variable for pipeline construction. If a p-diameter pipeline is built from shale gas source b to b' in period t, $Bc_{b,p,t,b'}^p = 1$, otherwise it is 0.

$$C_t^p = \sum_{b\in B}\sum_{p\in P}\sum_{b'\in B}c_p^p\cdot Bc_{b,p,t,b'}^p\cdot dis_{b,b'} \quad \forall t\in T \tag{4}$$

The construction cost of processing stations (C_t^{ps}) depends on the type of processing stations. $Bc_{b,s,t}^{ps}$ is the binary variable for the construction of a processing station, if a s-type processing station is built in gas sources b in period t, $Bc_{b,s,t}^{ps} = 1$, otherwise it is 0.

$$C_t^{ps} = \sum_{b\in B}\sum_{s\in S}cc_s^{ps}\cdot Bc_{b,s,t}^{ps} \quad \forall t\in T \tag{5}$$

Similarly, the construction cost of extending processing stations (Ce_t^{ps}) can be calculated by the following formula. If the original s-type processing station is expanded in gas sources b in period t, $Bec_{b,s,t}^{ps} = 1$, otherwise it is 0.

$$Ce_t^{ps} = \sum_{b\in B}\sum_{s\in S}cc_s^{ps}\cdot Bec_{b,s,t}^{ps} \quad \forall t\in T \tag{6}$$

The total operation cost of processing stations (Ct_t^{ope}) in period t is equal to the sum of the operation costs in each gas source b.

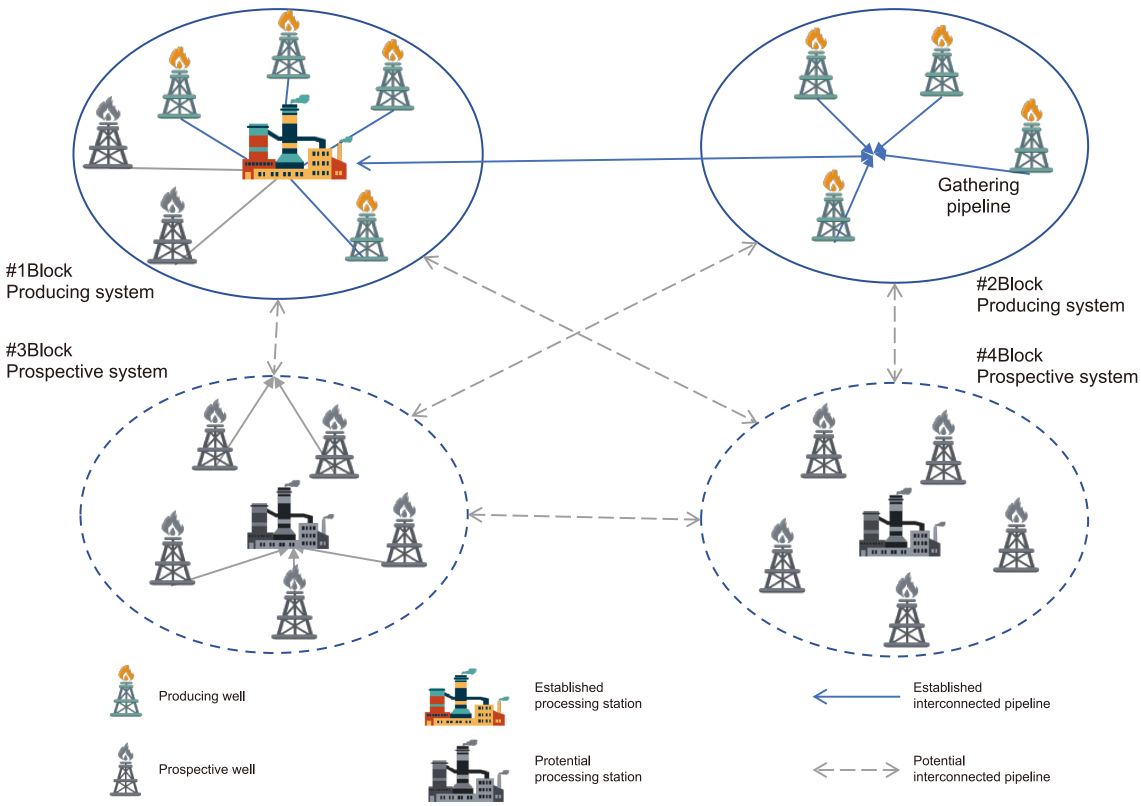

Fig. 1. Illustration of the new operation mode based on processing capacity allocation.

$$Ct_t^{ope} = \sum_{b\in B} C_{b,t}^{ope} \quad \forall t \in T \tag{7}$$

The operation cost of each gas source b ($C_{b,t}^{ope}$) comprises fixed cost and variable cost. $B_{b,s,t}^{ps}$ is the binary variable of processing stations. If there is an available s-type processing station in shale gas source b in period t, $B_{b,s,t}^{ps} = 1$, otherwise it is 0. $Bec_{b,s,t}^{ps}$ is the binary variable of expanded processing stations. If there is an available expanded s-type processing station in shale gas source b in period t, $Bec_{b,s,t}^{ps} = 1$, otherwise it is 0.

$$C_{b,t}^{ope} = \sigma_t \cdot \left(\sum_{s\in S} c_s^{fix} \cdot B_{b,s,t}^{ps} + \sum_{s\in S} c_s^{fix} \cdot Bec_{b,s,t}^{ps} + co \cdot Q_{b,t} \right) \ \forall b \in B, \ t\in T \tag{8}$$

where c_s^{fix} is the fixed operation cost of s-type processing station, co is the processing cost of raw shale gas per unit, $Q_{b,t}$ is the flowrate that needs to be processed in block b of gas source in period t. The flowrate allocation cost (C_t^{fl}) is related to the unit delivery cost ($c_{b,b'}^q$) and flowrate ($Q_{b,t,b'}^{pipe}$), which means the flowrate from block b to b' in period t.

$$C_t^{fl} = \sigma_t \cdot \sum_{b\in B} \sum_{b'\in B} c_{b,b'}^q \cdot Q_{b,t,b'}^{pipe} \quad \forall t \in T \tag{9}$$

3.2. Interconnected pipeline construction

$B_{b,p,t,b'}^p$ is the binary variable of interconnected pipelines. If there is an available p-diameter pipeline in shale gas source b to b' in period t, $B_{b,p,t,b'}^p = 1$, otherwise it is 0. If there is already an interconnected p-diameter pipeline between shale gas source b and b' in the initial period ($be_{b,p,b'}^p = 1$), then the pipeline is available for flowrate allocation ($B_{b,p,t,b'}^p = 1$). This also means that there is no need to construct new pipelines ($Bc_{b,p,t,p'}^p = 0$).

$$\begin{aligned} &1 + M\cdot\left(be_{b,p,b'}^p - 1\right) \le B_{b,p,t,b'}^p \quad \forall b, \ b' \in B, \ p \in P, \ t = 0 \\ &B_{b,p,t,b'}^p \le 1 + M\cdot\left(1 - be_{b,p,b'}^p\right) \quad \forall b, \ b' \in B, \ p \in P, \ t = 0 \end{aligned} \tag{10}$$

$$\begin{aligned} &M\cdot\left(be_{b,p,b'}^p - 1\right) \le Bc_{b,p,t,b'}^p \quad \forall b, \ b' \in B, \ p \in P, \ t \in T \\ &Bc_{b,p,t,p'}^p \le M\cdot\left(1 - be_{b,p,b'}^p\right) \quad \forall b, \ b' \in B, \ p \in P, \ t \in T \end{aligned} \tag{11}$$

Only one pipeline can be built between the two gas sources, and the construction time and pipeline diameter are determined.

$$\sum_{p\in P}\sum_{t\in T} Bc_{b,p,t,b'}^p + \sum_{p\in P}\sum_{t\in T} Bc_{b',p,t,b}^p \le 1 \quad \forall b, \ b' \in B \tag{12}$$

In addition, the construction of the interconnected pipeline takes a certain amount of time (tp). Therefore, the new pipeline cannot be built at the end of the planning time horizon because the construction is too late to be completed on time.

$$Bc_{b,p,t,b'}^p = 0 \quad \forall b, \ b' \in B, \ p \in P, \ T - tp < t \le T \tag{13}$$

Before the completion of the construction of the interconnected pipeline ($t'+tp$), the pipeline does not exist, and it cannot be used for flowrate allocation until the construction is completed.

$$B^{p}_{b,p,t,b'} \le M\cdot\left(1-Bc^{p}_{b,p,t',b'}\right) \ \forall b,\ b'\in B,\ p\in P,\ t,\ t'\in T,\ t<t'+tp \tag{14}$$

$$\begin{aligned}1+M\cdot\left(Bc^{p}_{b,p,t,b'}-1\right)\le B^{p}_{b,p,t+tp,b'} \ \forall b,\ b'\in B,\ p\in P,\ 0\le t\le T-tp\\ 1+M\cdot\left(1-Bc^{p}_{b,p,t,b'}\right)\ge B^{p}_{b,p,t+tp,b'} \ \forall b,\ b'\in B,\ p\in P,\ 0\le t\le T-tp\end{aligned} \tag{15}$$

The available interconnected pipeline over the period t originates from the original existing or is built later and complete at this period.

$$B^{p}_{b,p,t,b'} \le \sum_{t'\in T} Bc^{p}_{b,p,t',b'} + be^{p}_{b,p,b'} \quad \forall b,\quad b'\in B,\quad p\in P,\quad t\in T \tag{16}$$

Once the construction of the interconnected pipelines is completed, it will remain available in the subsequent period.

$$B^{p}_{b,p,t,b'} \le B^{p}_{b,p,t+1,b'} \quad \forall b, b'\in B,\quad p\in P,\quad 0\le t<T \tag{17}$$

There is only one available interconnected pipeline between shale gas source b and b'.

$$B^{p}_{b,p,t,b'} + B^{p}_{b',p,t,b} \le 1 \quad \forall b,\quad b'\in B,\quad p\in P,\quad t\in T \tag{18}$$

$$B^{p}_{b,p,t,b'} = 0 \quad \forall b,\quad b'\in B,\quad b=b',\quad p\in P,\quad t\in T \tag{19}$$

The construction of interconnected pipelines needs to avoid geographical obstacles. $ob_{b,b'}$ is a binary parameter of pipeline path obstacles. If there are obstacles between shale gas source b and b', $ob_{b,b'}=1$, otherwise it is 0.

$$\begin{aligned}M\cdot\left(1-ob_{b,b'}\right)\ge Bc^{p}_{b,p,t,b'} \quad \forall b,\quad b'\in B,\quad p\in P,\quad 0\le t<T\\ Bc^{p}_{b,p,t,b'}\ge M\cdot\left(ob_{b,b'}-1\right) \quad \forall b,\quad b'\in B,\quad p\in P,\quad 0\le t<T\end{aligned} \tag{20}$$

3.3. Processing station construction

If there is already a s-type processing station at shale gas source b in the initial period ($be^{ps}_{b,s}=1$), then the processing station ($B^{ps}_{b,s,t}=1$) can be used to process raw shale gas.

$$\begin{aligned}1+M\cdot\left(be^{ps}_{b,s}-1\right)\le B^{ps}_{b,s,t} \quad \forall b\in B,\quad s\in S,\quad t=0\\ B^{ps}_{b,s,t}\le 1+M\cdot\left(1-be^{ps}_{b,s}\right) \quad \forall b\in B,\quad s\in S,\quad t=0\end{aligned} \tag{21}$$

If the shale gas source b has a s-type processing station ($be^{ps}_{b,s}=1$) in the initial period, there is no need to build a new processing station ($Bc^{ps}_{b,s,t}=0$), but it can be expanded later.

$$\begin{aligned}M\cdot\left(be^{ps}_{b,s}-1\right)\le Bc^{ps}_{b,s,t} \quad \forall b\in B,\quad s\in S,\quad t\in T\\ Bc^{ps}_{b,s,t}\le M\cdot\left(1-be^{ps}_{b,s}\right) \quad \forall b\in B,\quad s\in S,\quad t\in T\end{aligned} \tag{22}$$

If a processing station needs to be built, the construction type and construction period are determined.

$$\sum_{s\in S}\sum_{t\in T} Bc^{ps}_{b,s,t}\le 1 \quad \forall b\in B \tag{23}$$

The type of processing station that has been built in the shale gas source b is unique.

$$\sum_{s\in S} Bc^{ps}_{b,s,t}\le 1 \quad \forall b\in B, t\in T \tag{24}$$

Same as pipelines, the construction of the processing station requires a certain amount of time (tk), so the processing station cannot be built at the end of the planning time horizon.

$$Bc^{ps}_{b,s,t}=0 \quad \forall b\in B,\quad s\in S, T-tK<t\le T \tag{25}$$

Before the completion of the construction of the processing station (t'+tk), the processing station does not exist, and it cannot be available until the construction is completed.

$$B^{ps}_{b,s,t}\le M\cdot\left(1-Bc^{ps}_{b,s,t'}\right) \ \forall b\in B,\quad s\in S,\quad t,\quad t'\in T,\quad t<t'+tk \tag{26}$$

$$\begin{aligned}1+M\cdot\left(Bc^{ps}_{b,s,t}-1\right)\le B^{ps}_{b,s,t+tk} \ \forall b\in B,\quad s\in S,\quad 0\le t\le T-tk\\ 1+M\cdot\left(1-Bc^{ps}_{b,s,t}\right)\ge B^{ps}_{b,s,t+tk} \quad \forall b\in B,\quad s\in S,\quad 0\le t\le T-tk\end{aligned} \tag{27}$$

The available processing station over the period t originate from the original existing or are built later and complete at this period.

$$B^{ps}_{b,s,t}\le \sum_{t'\in T} Bc^{ps}_{b,s,t'} + be^{ps}_{b,s} \ \forall b\in B,\quad s\in S,\quad t\in T \tag{28}$$

Once the construction of the processing stations is completed, it will remain available in the subsequent period.

$$B^{ps}_{b,s,t}\le B^{ps}_{b,s,t+1} \quad \forall b\in B,\quad s\in S,\quad 0\le t<T \tag{29}$$

3.4. Processing station expansion

Only established processing stations can be expanded to increase the ability to process wellhead raw shale gas. $Bec^{ps}_{b,s,t}$ is the binary variable for the expansion construction of processing stations. If a s-type processing station is expanded in gas source block b in period t, $Bec^{ps}_{b,s,t}=1$ and otherwise it is 0.

$$Bec^{ps}_{b,s,t}\le \sum_{t'=0}^{t} B^{ps}_{b,s,t'} \quad \forall b\in B,\quad s\in S,\quad t\in T \tag{30}$$

The established processing stations can only be expanded once at most, and the time and type of expansion are determined. $Be^{ps}_{b,s,t}$ is the binary variable of expanded processing stations. If there is an available expanded s-type processing station in gas source block b in period t, $Be^{ps}_{b,s,t}=1$ and otherwise it is 0.

$$\sum_{s\in S}\sum_{t\in T} Bec^{ps}_{b,s,t}\le 1 \quad \forall b\in B \tag{31}$$

$$\sum_{s\in S} Be^{ps}_{b,s,t}\le 1 \quad \forall b\in B,\quad t\in T \tag{32}$$

Similarly, the expansion time, completion time and status of expanded processing stations can be described by the following Eqs. (33)–(35), respectively.

$$Bec^{ps}_{b,s,t}=0 \quad \forall b\in B,\quad s\in S,\quad T-tk<t\le T \tag{33}$$

$$1 + M\cdot\left(Bec^{ps}_{b,s,t} - 1\right) \le Be^{ps}_{b,s,t+tk} \quad \forall b \in B, \quad s \in S, \quad 0 \le t \le T - tk$$
$$1 + M\cdot\left(1 - Bec^{ps}_{b,s,t}\right) \ge Be^{ps}_{b,s,t+tk} \quad \forall b \in B, \quad s \in S, \quad 0 \le t \le T - tk \tag{34}$$

$$Bec^{ps}_{b,s,t} \le M\cdot\left(1 - Bec^{ps}_{b,s,t'}\right) \quad \forall b \in B, \quad s \in S, \quad t, \quad t' \in T, \quad t < t' + tk \tag{35}$$

The established processing stations will only have additional processing capacity ($Be^{ps}_{b,s,t} = 1$) after expansion ($Bec^{ps}_{b,s,t'} = 1$).

$$Be^{ps}_{b,s,t} \le \sum_{t' \in T} Bec^{ps}_{b,s,t'} \quad \forall b \in B, \quad s \in S, \quad t \in T \tag{36}$$

Once the expansion of established processing stations is completed, the added processing capacity will remain available in the subsequent period.

$$Be^{ps}_{b,p,t} \le Be^{ps}_{b,p,t+1} \quad \forall b \in B, \quad p \in P, \quad 0 \le t < T \tag{37}$$

3.5. Processing stations capacity

The maximum processing capacity of the processing station ($Q^{max}_{b,t}$) is the sum of the capacity obtained from the initial construction ($Q^{c\ max}_{b,t}$) and the capacity obtained from the subsequent expansion ($Qex^{max}_{b,t}$).

$$Q^{max}_{b,t} = Q^{c\ max}_{b,t} + Qex^{max}_{b,t} \quad \forall b \in B, \quad t \in T \tag{38}$$

The processing capacity obtained from the initial construction and subsequent expansion depends on the type of processing stations.

$$qc_s + M\cdot\left(B^{ps}_{b,s,t} - 1\right) \le Q^{cmax}_{b,t} \quad \forall b \in B, \quad t \in T, \quad s \in S$$
$$Q^{cmax}_{b,t} \le qc_s + M\cdot\left(1 - B^{ps}_{b,s,t}\right) \quad \forall b \in B, \quad t \in T, \quad s \in S \tag{39}$$

$$qc_s + M\cdot\left(Be^{ps}_{b,s,t} - 1\right) \le Qex^{max}_{b,t} \quad \forall b \in B, \quad t \in T, \quad s \in S$$
$$Qex^{max}_{b,t} \le qc_s + M\cdot\left(1 - Be^{ps}_{b,s,t}\right) \quad \forall b \in B, \quad t \in T, \quad s \in S \tag{40}$$

If there is no processing station built in the block, and no processing station is expanded, the corresponding processing capacity is 0.

$$Q^{cmax}_{b,t} \le M\cdot\sum_{s\in S} B^{ps}_{b,s,t} \quad \forall b \in B, \quad t \in T$$
$$Qex^{max}_{b,t} \le M\cdot\sum_{s\in S} Be^{ps}_{b,s,t} \quad \forall b \in B, \quad t \in T \tag{41}$$

The flowrate that needs to be processed ($Q_{b,t}$) should be less than the maximum processing capacity of the processing station in this block.

$$Q_{b,t} \le Q^{max}_{b,t} \quad \forall b \in B, \quad t \in T \tag{42}$$

3.6. Flowrate allocation

Flowrate can be scheduled between blocks through the interconnected pipelines. The relationship of the processed flowrate ($Q_{b,t}$), the production flowrate ($Q^{pro}_{b,t}$) and the scheduled flowrate ($Q^{pipe}_{b,t,b'}$) is expressed as follows:

$$Q_{b,t} = Q^{pro}_{b,t} + \sum_{b' \in B} Q^{pipe}_{b',t,b} - \sum_{b' \in B} Q^{pipe}_{b,t,b'} \quad \forall b \in B, \quad t \in T \tag{43}$$

The production flowrate of gas source block is the sum of each shale gas well site. $q^{w}_{b,w,t}$ is planned production of shale gas well sites w in gas source block b in period t, $\gamma_{b,t}$ is a coefficient to characterize the difference between actual output and planned output.

$$Q^{pro}_{b,t} = \sum_{w\in W} \gamma_{b,t}\cdot q^{w}_{b,w,t} \quad \forall b \in B, \quad t \in T \tag{44}$$

Flowrate allocation can only be carried out when the block has interconnected pipelines to other blocks, otherwise, the raw shale gas of well site can only be processed in this block. $B^{qto}_{b,t,b'}$ is the binary variable of allocation directions. If shale gas flow from source block b to b' in period t, $B^{qto}_{b,t,b'} = 1$ and 0 otherwise.

$$B^{qto}_{b,t,b'} \le \sum_{p\in P} B^{p}_{b,p,t,b'} + \sum_{p\in P} B^{p}_{b'p,t,b} \quad \forall b, \quad b' \in B, \quad t \in T \tag{45}$$

Flowrate allocation only exists between different blocks, and the allocation direction in the same period is determined.

$$B^{qto}_{b,t,b'} + B^{qto}_{b',t,b} \le 1 \quad \forall b, \quad b' \in B, \quad b \ne b', \quad t \in T \tag{46}$$

$$B^{qto}_{b,t,b'} = 0 \quad \forall b, \quad b' \in B, \quad b = b', \quad t \in T \tag{47}$$

Only when flowrate allocation is performed, there is an allocation output from block b to block b'.

$$Q^{pipe}_{b,t,b'} \le M\cdot B^{qto}_{b,t,b'} \quad \forall b, \quad b' \in B, \quad t \in T \tag{48}$$

The flowrate cannot exceed the delivery capacity of interconnected pipeline.

$$Q^{pipe}_{b,t,b'} \le q^{p}_{p} + M\cdot\left(1 - \left(B^{p}_{b,p,t,b'} + B^{p}_{b',p,t,b}\right)\right) \quad \forall b, \quad b' \in B, \quad b \ne b', \quad p \in P, \quad t \in T \tag{49}$$

In conclusion, the proposed optimization model based on flowrate allocation aims at maximizing the NPV of Eq. (1) and is subject to the constraints of Eqs. (2)–(49). Moreover, when using the conventional method without flowrate allocation, the following two constraints need to be added. When the flowrate allocation is not carried out, there is no need to build an interconnected pipeline and no allocation operation is required.

$$Bc^{p}_{b,p,t,b'} = 0 \quad \forall b, \quad b' \in B, \quad p \in P, \quad t \in T \tag{50}$$

$$B^{qto}_{b,t,b'} = 0 \quad \forall b, \quad b' \in B, \quad t \in T \tag{51}$$

4. Case study

In this section, the proposed model is applied to a natural gas field in Sichuan, China on a monthly time scale to demonstrate the feasibility and advantages of the proposed model, and compared with the conventional method without processing capacity allocation. The case study was implemented on a computer with a 4.00 GHz 8-core Intel Core i7-4790 processor using GAMS programming language and Gurobi solver (Hong et al., 2019, 2020a).

4.1. Basic data

The data required in the case study are sourced from actual engineering provided by PipeChina Beijing Pipeline. In addition, due to confidentiality reasons, some data have been reasonably modified according to privacy policies. The natural gas field to be developed is shown in Fig. 2. There are 4 gas source blocks and each source block contains 9 to 15 well sites, for a total of 47 well sites but no processing station exists. Those 4 gas source blocks form 4 gathering production systems (i1, i2, i3, i4). Taking one month as the time scale, gas reservoir engineers provide a 10-year life-cycle productivity prediction profiles for different types of gas well fields in each block, as shown in Fig. 3. There are multiple types of gas well production curves in different blocks, and some gas wells in the same block have the same gas well production curve. In addition, the production rate in each period is constant, and the 20-year development production plan for the gas field is shown in Appendix Fig. A1. As a result, there are 240 periods ($t = 1, 2 \ldots 240$) in total and each period has 30 working days (δ_t).

Based on the 8% annual rate of the Chinese pipeline industry, the rate of return on capital (r) is set as 0.67% per month. Fig. 4 provides the qualified natural gas prices (p_t) for different periods. It is assumed that the composition of raw natural gas produced from the wellhead in this gas field is consistent regardless of the location of the gas well, and all qualified natural gas produced in the gas field can be sold. Moreover, the produced raw natural gas can be processed by constructing a processing station in its block, or it can be transported to the remaining blocks for processing through the block interconnected pipeline to satisfy the quality requirements. There are five different processing stations as shown in Appendix Table A1. The relevant parameters related to four different pipelines are summarized in Appendix Table A2. To

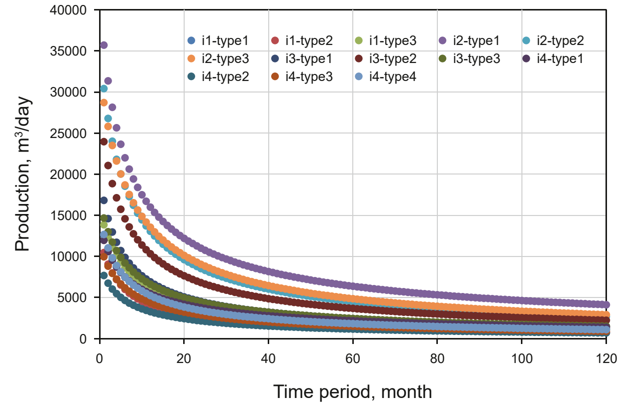

Fig. 3. Monthly production profile of each gas source block.

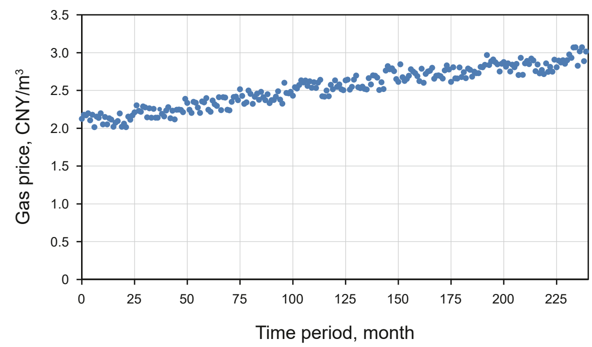

Fig. 4. The price of qualified natural gas in different time periods.

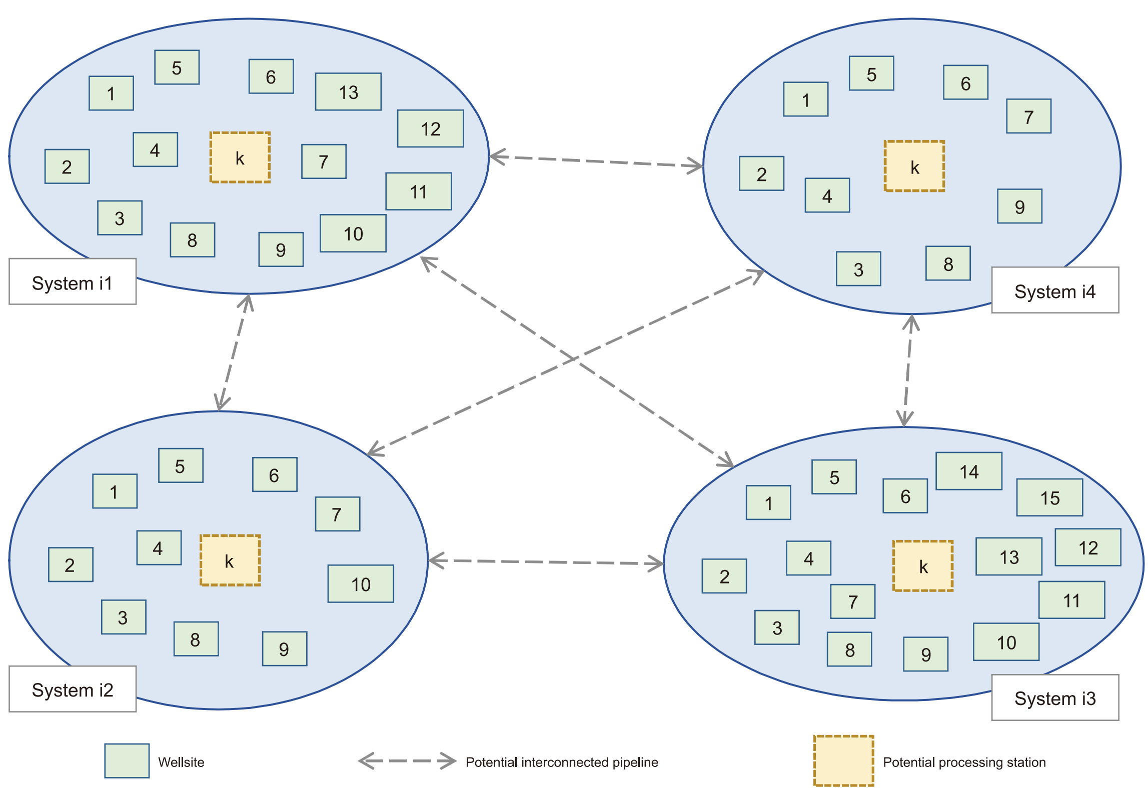

Fig. 2. Operation optimization of multi-system during gas field multi-stage development.

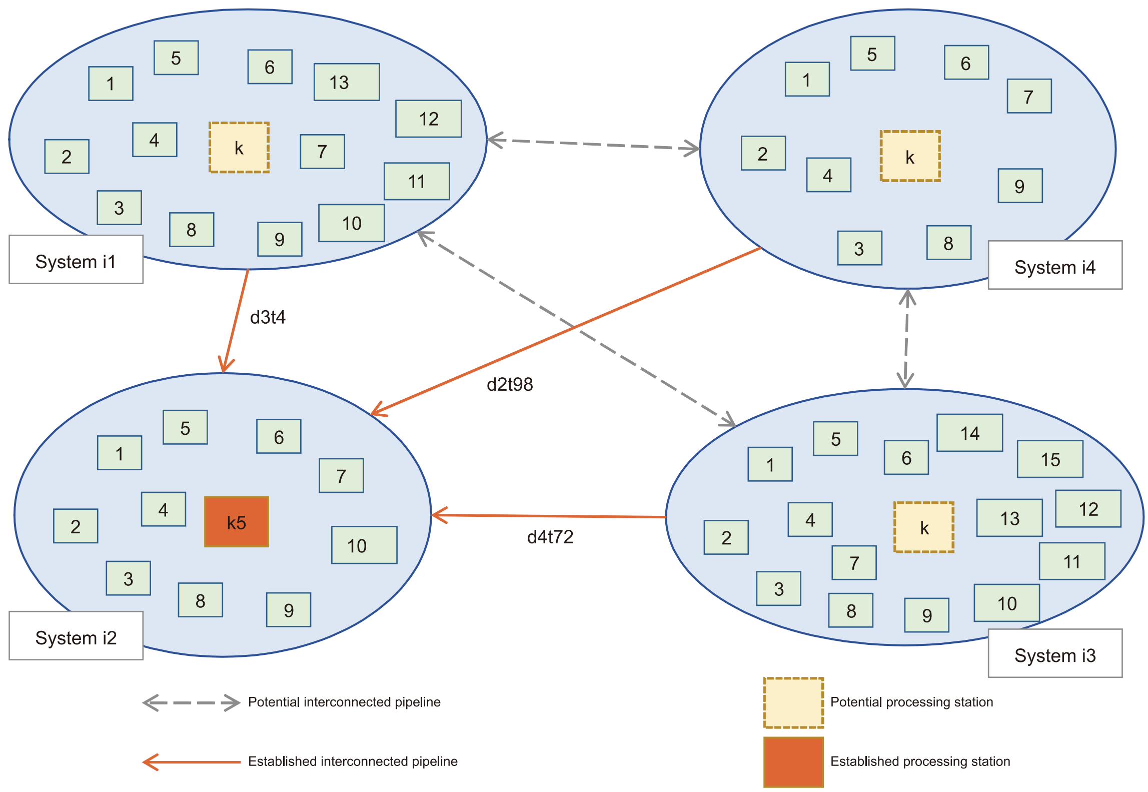

Fig. 5. Schematic diagram of the optimal construction for the multi-system based on processing capacity allocation.

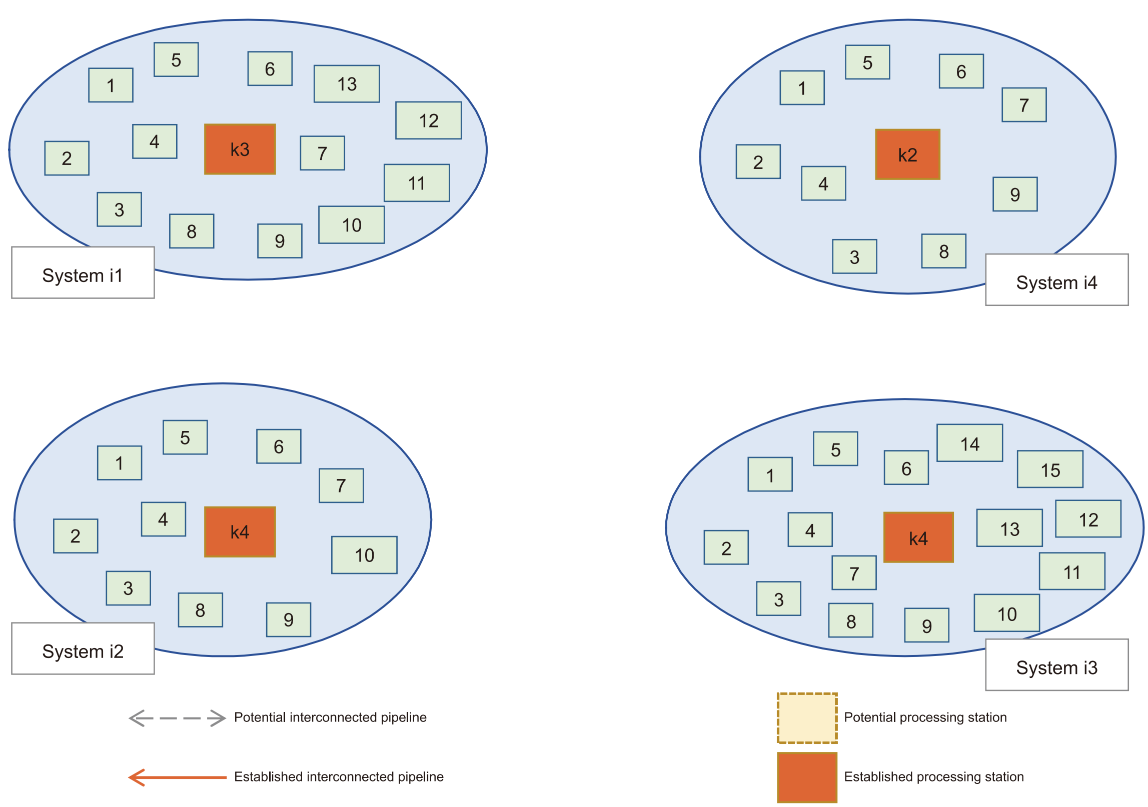

Fig. 6. Schematic diagram of the optimal construction for the multi-system without processing capacity allocation.

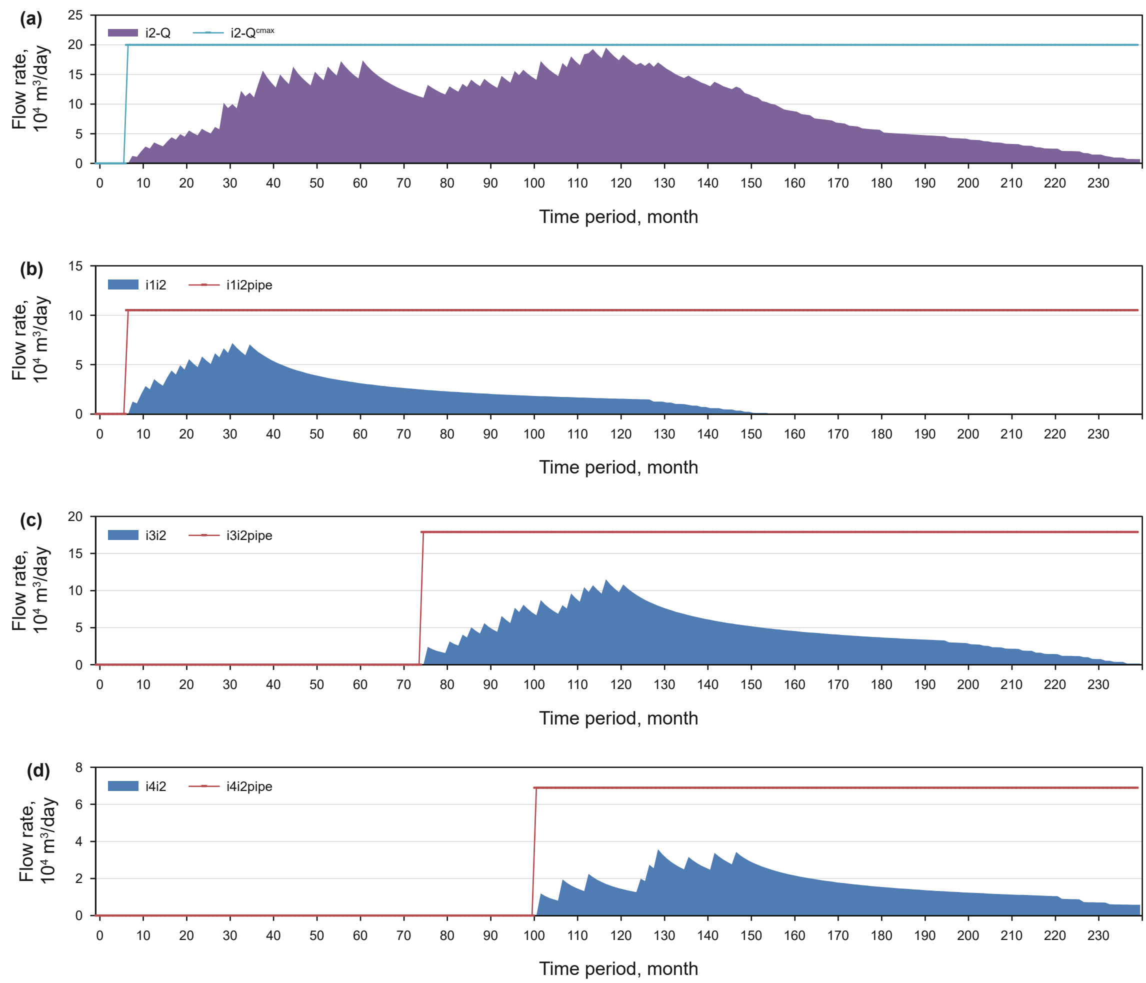

Fig. 7. Utilization of processing stations and pipelines of multi-system based on processing capacity allocation, (**a**) i2 processing stations, (**b**) pipeline from i1 to i2, (**c**) pipeline from i3 to i2, (**d**) pipeline from i4 to i2.

better present the advantage of the proposed optimization model, it is compared with the conventional method without processing capacity allocation, where all parameters are set to be consistent with the proposed optimization model except for two constraints (50) and (51).

4.2. Results and discussion

4.2.1. Gas field construction scheme

The optimal gas field construction scheme based on processing capacity allocation is shown in Fig. 5. Only a k5-type process processing station is needed to be built in the i2 block, and the raw natural gas produced in other blocks will be transported to the i2 block for unified treatment by interconnected pipelines. Specifically, although the gas well sites of the i1 block only start production in the 6th period, considering the construction time of the project, the i2 block needs to build a *k5*-type processing station with a processing capacity of 2.0×10^5 m^3/day in the first period in advance. Similarly, three interconnected pipelines are required, including a DN80 pipeline from the i1 block to the i2 block in the 4th period (d3t4), a DN100 pipeline from the i3 block to the i2 block in the 72nd period(d4t72), and a DN65 pipeline from the i4 block to the i2 block in the 98th period (d2t98). However, if there is no processing capacity allocation as shown in Fig. 6, it is necessary to establish corresponding processing stations in each block to process the raw natural gas produced in each block. The construction schemes of processing stations are 1.0×10^5 m^3/day for the i1 block, 1.5×10^5 m^3/day for the i2 block in 22nd period, 1.5×10^5 m^3/day for the i3 block in 69th period and 5×10^4 m^3/day for the *i5* block in 95th period.

4.2.2. Utilization efficiency of pipelines and processing devices

When the processing capacity allocation approach is adopted, the utilization of processing stations and pipelines in multi-system is shown in Fig. 7, where the shaded area is the actual flow rate of the processing stations or pipelines, and the solid line is the maximum capacity of the processing stations or pipelines. It can be found that the processing station of the i2 block has sufficient processing capacity to ensure the processing of raw natural gas during the development, and the remaining interconnected pipelines also have sufficient transmission capacity for processing capacity allocation between blocks. Fig. 8 shows the utilization of multi-system processing stations for the conventional method without processing capacity allocation, and

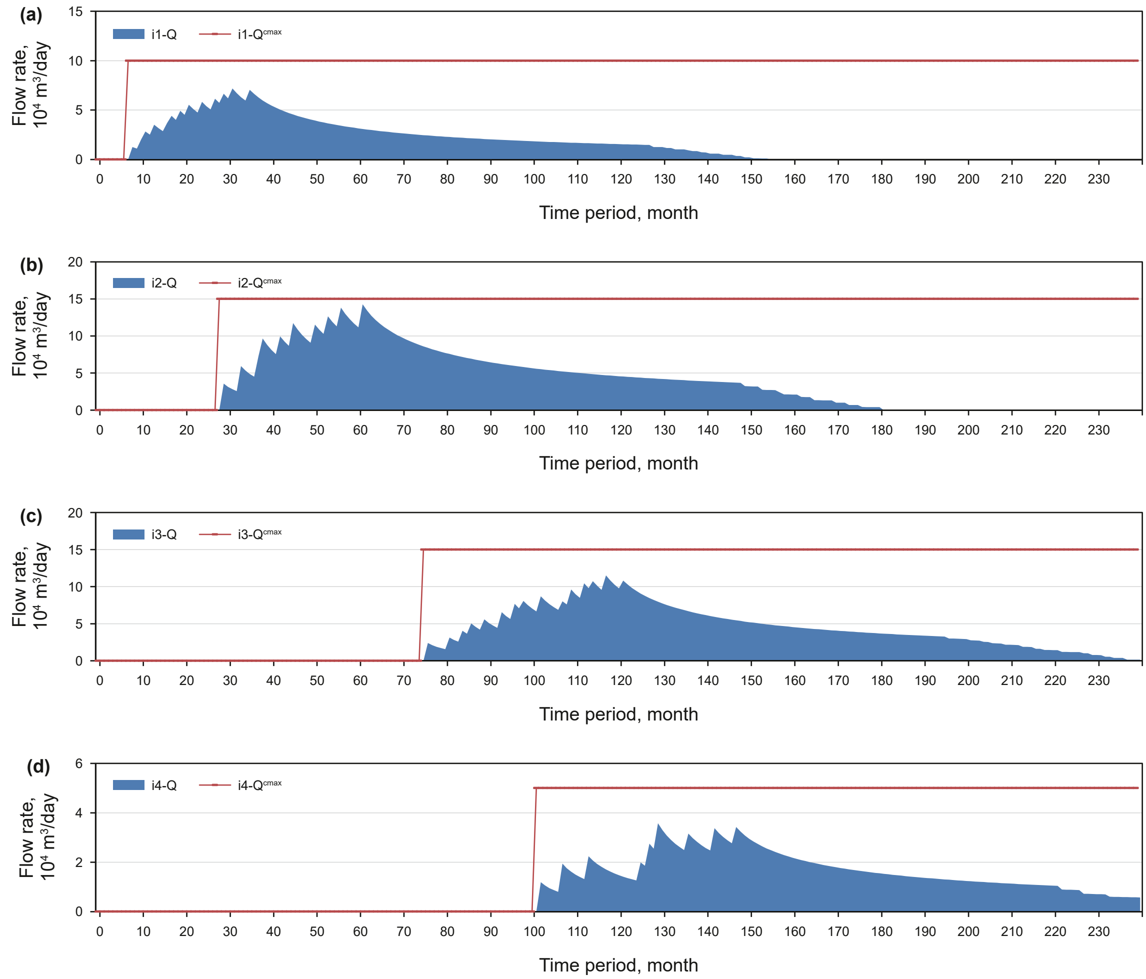

Fig. 8. Utilization of processing stations of multi-system without processing capacity allocation, (**a**) i1 system, (**b**) i2 system, (**c**) i3 system, (**d**) i4 system.

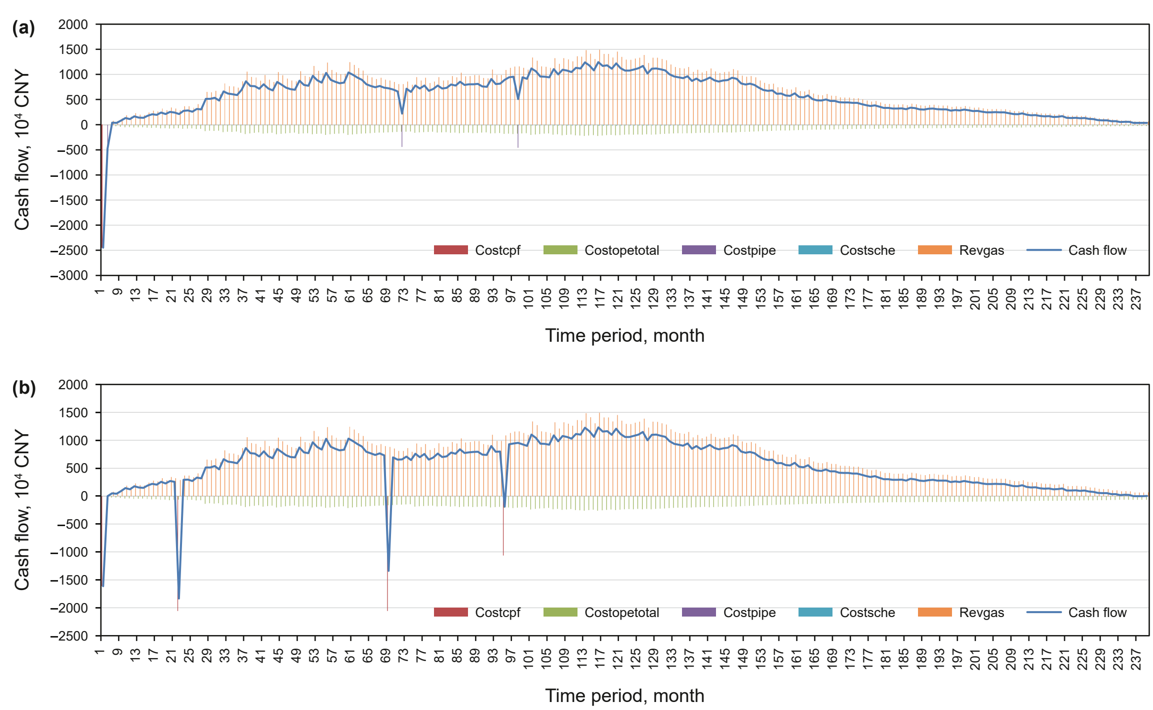

Fig. 9. Economic outlook based on production allocation, (**a**) processing capacity allocation approach, (**b**) conventional method.

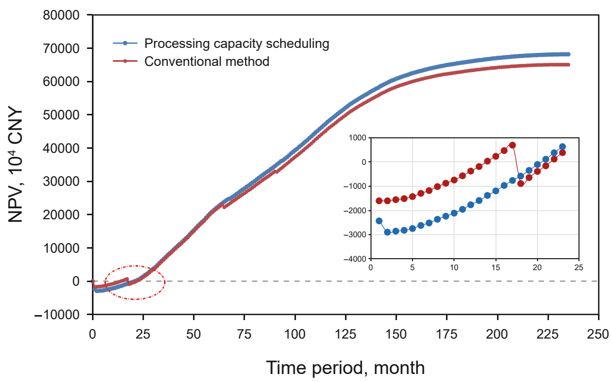

Fig. 10. Comparison of cumulative NPV in different periods.

the processing stations in each block also have sufficient processing capacity. However, there are significant differences in device utilization between the two methods. In this paper, the load factor index (Hong et al., 2020b) is employed to characterize the utilization efficiency of the processing station, which is the actual flowrate to the maximum capacity, i.e., the ratio of the shaded area to the area surrounded by the solid line in Figs. 7 and 8. The results show that the processing capacity allocation method can maintain a higher average utilization efficiency of processing equipment than the conventional method. More specifically, it increases the average utilization efficiency from 27.37% to 48.94%.

4.2.3. Economic comparison

The economic outlook of the processing capacity allocation approach and the conventional method is shown in Fig. 9. Firstly, compared with other expenditures, the construction cost of processing stations is the most expensive. Secondly, the economic pressure is less after the adoption of processing capacity allocation. Specifically, the cash flow is negative only in the first period due to the construction of the processing station in the i2 block. Although pipelines need to be built in subsequent periods, the sale of qualified natural gas in the gas field has been able to generate enough income already to make the cash flow positive. On the contrary, in the absence of processing capacity allocation, four negative cash flows occur during the construction of the processing station. Therefore, the use of processing capacity allocation can alleviate the financial pressure of the project.

The cumulative NPV of profits is shown in Fig. 10. First of all, the cumulative NPVs of the processing capacity allocation approach is both less than zero in the first 20 periods. This is because the construction of infrastructure (processing stations and pipelines) requires a lead time, and natural gas cannot be produced until the infrastructure is completed. Secondly, for the conventional method, the NPV is not greater than 0 until the 14th period, but due to the construction of the i2 processing station in the 18th period, the NPV in the 18th period becomes negative again, and then it remains less than 0 until the 22nd period. As for the processing capacity allocation approach, the NPV is always greater than 0 after the 21st period. Finally, the NPV of the conventional method is 6.5109×10^8 CNY, while the use of the processing capacity allocation approach increases the NPV by 4.8%–6.8233×10^8 CNY. Therefore, the application of the processing capacity allocation approach has a shorter investment payback period and a higher NPV of the project, which is conducive to obtaining better gas field development benefits.

4.2.4. Sensitivity analysis

To quantify the impact of gas production and gas prices on the final NPV, a sensitivity analysis has been performed and the results are shown in Fig. 11. First of all, both the increase in natural gas production and natural gas price will get a better optimal NPV, showing a positive correlation. Secondly, the impact of natural gas price change on the optimal NPV is greater than that of gas well productivity. Finally, As can be seen from Fig. 11(a), When the natural gas price rises by 35%, the optimal NPV of the conventional method and processing capacity allocation approach will increase by 47% and 45%, respectively. The processing capacity allocation approach requires significant initial investment in the construction of processing stations and pipelines, while it increases the utilization efficiency of processing stations, the cost savings from this efficiency gain might not be realized immediately. In addition, the processing capacity allocation approach, being more integrated and interconnected, might be more susceptible to market conditions, which could influence its NPV growth rate. However, it should be noted that under the same conditions, the economic results of the processing capacity allocation approach are better than the conventional method as can be seen from Fig. 11(b). To better consider the influence of parameter fluctuations, it is necessary to carry out optimization research based on stochastic programming.

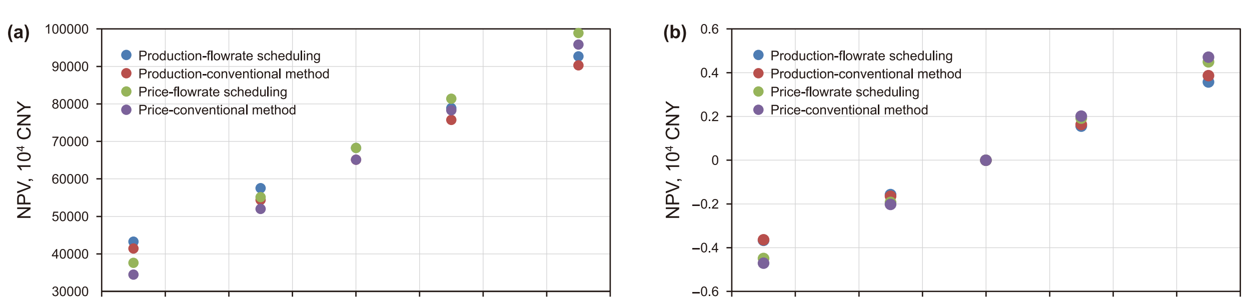

Fig. 11. Sensitivity analysis of gas production and gas prices.

5. Conclusions

This study proposes a novel operation mode for natural gas multiple production systems, which is based on processing capacity allocation via interconnected pipelines to improve production flexibility. The key findings and contributions are summarized as follows.

(1) **Novel Operation Mode**: a new operation mode based on processing capacity allocation through interconnected pipelines is proposed, which allows for the sharing of processing stations among multiple production systems, thereby improving production flexibility and operating efficiency.
(2) **Multi-Period MILP Model**: A multi-period MILP model is developed to assist decision-makers in devising operation plans for natural gas fields. The model considers processing capacity, location, construction timing, and capacity expansions of processing stations, as well as the transmission capacity of pipelines to meet long-term production demands.
(3) **Case Study**: The study provides a 20-year operation strategy for a gas field with 47 well sites, showcasing the benefits of the processing capacity allocation approach. Compared to the conventional method, the processing capacity allocation approach increases the average efficiency of processing equipment from 27.37% to 48.94%, reduces financial pressure with only one period of negative cash flow due to the construction of processing stations, and increases the NPV of the project by 4.8%, leading to better gas field development benefits.
(4) **Future Research**: The sensitivity analysis is conducted to investigate the effects of natural gas production and gas prices on the results. In future research, we will supplement and improve this work by considering the uncertainty-related factors based on stochastic programming to provide further insights. Moreover, we will consider stationary or skid-mounted compressors to improve the optimization model and investigate efficient solution algorithms.

Nevertheless, compared with previous methods, our method has made considerable progress and shows that the synergy between processing capacity allocation and infrastructure construction can increase potential profits.

CRediT authorship contribution statement

Bing-Yuan Hong: Investigation, Writing – original draft, Methodology, Data curation, Validation, Conceptualization, Writing – review & editing. **Zhi-Wei Chen:** Software, Investigation, Conceptualization, Writing – original draft, Methodology, Formal analysis. **Hai-Feng Chen:** Writing – review & editing, Software, Data curation, Writing – original draft, Methodology, Conceptualization. **Meng-Xi Zhou:** Writing – original draft, Validation, Methodology, Visualization, Resources, Investigation. **Jing Gong:** Writing – review & editing, Investigation, Methodology, Conceptualization. **Yu-Peng Xu:** Investigation, Writing – review & editing, Data curation, Conceptualization. **Zhen-Yu Zhu:** Writing – review & editing, Methodology, Resources, Software. **Xiao-Ping Li:** Methodology, Writing – review & editing, Visualization, Resources, Data curation, Writing – original draft, Software, Investigation, Conceptualization.

Declaration of competing interest

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

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Nomenclature

Indexes and sets

$p \in$ P	Pipeline diameters
$b,b' \in$ B	Shale gas source blocks
$w \in$ W	Shale gas well sites
$s \in S$	Processing stations
$t,t' \in T$	Time periods

Parameters

$be^{ps}_{b,s}$	If there is an available s-type processing station in shale gas source block b in the initial period, $be^{ps}_{b,s}=1$, otherwise it is 0. [0–1]
$be^{p}_{b,p,b'}$	If there is an available p-diameter pipeline from shale gas source block b to b' in the initial period, $be^{p}_{b,p,b'}=1$, otherwise it is 0. [0–1]
c^{ps}_{s}	Construction cost of s-type processing station [10^4CNY]
c^{fix}_{s}	Fixed operation cost of s-type processing station [10^4CNY]
co	Processing cost of raw shale gas per unit [10^4CNY/10^4m^3]
$c^{q}_{b,b'}$	Delivery cost of shale gas per unit from source block b to b' [10^4CNY/10^4m^3]
c^{p}_{p}	Construction cost of p-diameter pipeline per unit length [10^4CNY/km]
$dis_{b,b'}$	Distance from source block b to b' [km]
M	A maximum value
$ob_{b,b'}$	If there are obstacles between shale gas source block b and b', $ob_{b,b'}=1$, otherwise it is 0. [0-1]
p_t	Natural gas market price in period t [10^4CNY/10^4m^3]
qc_s	Maximum processing capacity of s-type processing station [10^4m^3/day]
$q^{w}_{b,w,t}$	Planned production of shale gas well sites w in gas source block b in period t [10^4m^3/day]
q^{q}_{p}	Maximum flowrate of p-diameter pipeline [10^4m^3/day]
tk	Lead time of s-type processing station [day]
tp	Lead time of p-diameter pipeline [day]
r	Discount rate [-]
μ	Conversion coefficient of wellhead raw shale gas to qualified pipeline gas [-]
σ_t	Working days in period t [day]
$\gamma_{b,t}$	Coefficient to characterize the difference between actual output and planned output in gas source block b in period t.

Binary decision variables

$Bc^{ps}_{b,s,t}$	If there is a s-type processing station is built in block b of gas source in period t, $Bc^{ps}_{b,s,t}=1$, otherwise it is 0.
$Bc^{p}_{b,p,t,b}$	If there is a pipeline with diameter p is built from block b of gas source to b' in period t, $Bc^{p}_{b,p,t,b}=1$, otherwise it is 0.
$Bc^{ps}_{b,s,t}$	If there is an available s-type processing station in block b of gas source in period t, $Bc^{ps}_{b,s,t}=1$, otherwise it is 0.

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$Bec^{\mathrm{ps}}_{b,s,t}$ If there is a s-type processing station is expanded in block b of gas source in period t, $Bec^{\mathrm{ps}}_{b,s,t}=1$, otherwise it is 0.

$Be^{\mathrm{ps}}_{b,s,t}$ If there is an extended s-type processing station available in block b of gas source in period t, $Be^{\mathrm{ps}}_{b,s,t}=1$, otherwise it is 0.

$B^{\mathrm{p}}_{b,p,t,b}$ If there is an available p-diameter pipeline in block b of gas source to b' in period t, $B^{\mathrm{p}}_{b,p,t,b}=1$, otherwise it is 0.

$B^{\mathrm{qto}}_{b,t,b'}$ If there is shale gas flow from gas source block b to b' in period t, $B^{\mathrm{qto}}_{b,t,b'}=1$, otherwise it is 0.

Continuous variables

CF_t Cash flow in period t [10^4CNY]

C^{ps}_t Construction cost of processing stations in period t [10^4CNY]

Ce^{ps}_t Construction cost of expanding processing stations in period t [10^4CNY]

$C^{\mathrm{ope}}_{b,t}$ Operation cost of processing stations in block b of gas source in period t [10^4CNY]

Ct^{ope}_t Operation cost of all processing stations in period t [10^4CNY]

C^{p}_t Construction cost of pipelines in period t [10^4CNY]

C^{fl}_t Flowrate allocation cost in period t [10^4CNY]

NPV Net present value [10^4CNY]

Rev_t Revenue of the sales of qualified pipeline gas [10^4CNY]

$Q_{b,t}$ The flowrate to be processed by the processing station in block b of gas source in period t [$10^4\mathrm{m}^3$/day]

$Q^{\mathrm{max}}_{b,t}$ Maximum processing capacity of the processing station in block b of gas source in period t [$10^4\mathrm{m}^3$/day]

$Q^{\mathrm{cmax}}_{b,t}$ Processing capacity gained by building processing stations in block b of gas source in period t [$10^4\mathrm{m}^3$/day]

$Qex^{\mathrm{max}}_{b,t}$ Additional processing capacity gained by expanding the processing station in block b of gas source in period t [$10^4\mathrm{m}^3$/day]

$Q^{\mathrm{pipe}}_{b,t,b'}$ Flowrate from gas source block b to b' in period t [$10^4\mathrm{m}^3$/day]

$Q^{\mathrm{pro}}_{b,t}$ Production rate of gas source block b in period t [$10^4\mathrm{m}^3$/day]

Appendix A

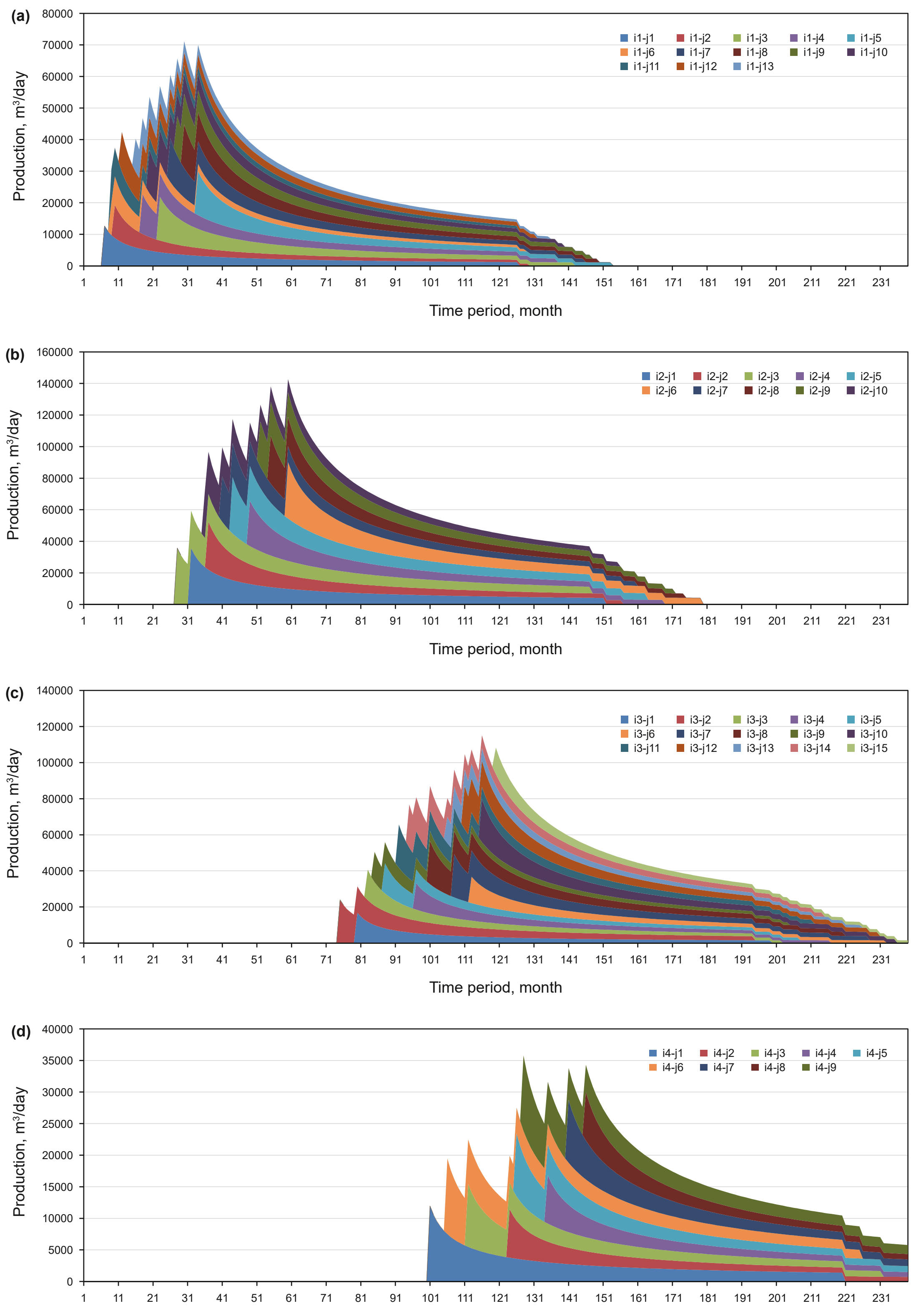

Fig. A1. 20-year development production plan for the gas field consisting 4 gas source blocks, (**a**) i1 block, (**b**) i2 block, (**c**) i3 block, (**d**) i4 block.

Table A1
Basic parameters of processing stations

	k1	k2	k3	k4	k5
Maximum processing capacity, 10^4Nm^3/day	3	5	10	15	20
Lead time, time periods	6	6	6	6	6
Construction cost, 10^4CNY	783	1065	1614	2058	2446
Fixed operating cost, 10^4CNY/day	0.22	0.30	0.45	0.57	0.68
Unit processing cost, 10^4CNY/10^4Nm^3	0.35	0.35	0.35	0.35	0.35

Table A2
Parameters related to interconnected pipelines

	d1(DN50)	d2(DN65)	d3(DN80)	d4(DN100)
Outside diameter, mm	60.3	73	88.9	114.3
Wall thickness, mm	3.18	3.58	3.96	4.37
Maximum delivery capacity, 10^4m^3/day	3.1	6.9	10.5	17.9
Lead time time, periods	3	3	3	3
Construction cost, 10^4CNY/km	37.33	41.73	47.77	55.23

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