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Conventional Natural Gas Project Investment and Decision Making under Multiple Uncertainties

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Abstract: Similar to many energy projects, the evaluation of investments in natural gas projects is influenced by technical and economic uncertainties. These uncertainties include natural resource characteristics, production, decline laws, prices, taxes, benchmark yield, and so on. In China, conventional natural gas is still the dominant energy source. The investors are mainly large state-owned energy companies. Therefore, it is necessary to include the technical and economic uncertainties, as well as the investment decision and optimization problems of the enterprises in a unified analytical framework. To this end, this paper innovatively constructs such a framework. Using numerical simulations of approaches, the process of investment decision optimization by companies based on technology assessment and price forecasting is visualized in detail. The results suggest that the investment decision of the enterprise needs to consider technical and economic uncertainties in an integrated manner. It also needs to combine the business strategy and social responsibility of the enterprise in order to construct the objective function. With the availability of data, the framework and its algorithms can be used for practical evaluation of investment plans and decision supports for conventional natural gas projects. The framework can also integrate the analytical perspective of the macroeconomic and political environment to bring in a more comprehensive range of uncertainties.

Keywords: natural gas project; technology and economy; uncertainties; economic evaluation; numerical simulation

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1. Introduction

As a clean, efficient and low-carbon fuel, natural gas is an important energy source for many countries. Since 2000, China's natural gas production and consumption have maintained rapid growth. In 2020, China's natural gas consumption is 12×10^{16} joules, and natural gas production is 194 billion cubic meters, an increase of approximately 275% and 125%, respectively, compared to 2009 [1]. Notably, the share of natural gas in primary energy consumption rose from 3.3% to 8.2% during the period [1]. From January to October 2022, China's apparent consumption of natural gas was 299.93 billion cubic meters [2]. From January to February 2023, the country's total natural gas production reached 37.2 billion cubic meters [3]. Of note is the positive role of natural gas in achieving carbon neutrality around 2050. One reason is that the process of reducing carbon emissions is gradual [4]. In this process, the use of renewable and green energy sources will not increase rapidly. Electricity still needs to rely on fossil energy sources, such as oil and natural gas, for conversion. Similar to hydroelectricity, their energy supply is less stable [5]. Of course, centralized power generation facilities and technical means can effectively control carbon emissions, through means such as co-generation and gas-fired power peak shaving and carbon capture and storage (CCS) [6]. Another reason is that natural gas has lower greenhouse gas emissions than coal and oil. This has positive implications for restructuring China's coal-based energy mix and reducing carbon emissions [7]. Natural gas is playing an increasingly important role in China's energy structure, which also makes the impact of natural gas demand, supply, price, cost, carbon emission, environmental protection, and other factors important to gradually introduce into the standardized energy economy and energy project management research [8–10].

At the same time, the development of energy technology over the past few decades has dramatically changed the global energy structure. It has two structural impacts on the demand for natural gas. First, advances in technology have led to greater use of unconventional natural gas resources such as shale and tight gas, which has resulted in more gas being produced and sourced at a lower price [11]. Second, the vigorous development of renewable energy sources, such as wind and solar, has led to the replacement of natural gas to some extent. For example, the widespread use of new energy buses, such as electric and hydrogen, has replaced buses using compressed natural gas (CNG) in China's urban bus systems. While Europe and North America continue to drive this energy mix transition, demand for natural gas in emerging economies, Asian countries, and especially China remains strong.

However, China's natural gas dependence on foreign countries is high, and domestic resources supply is limited. In 2020, the share of natural gas imports in China was 41% [1] because China's natural gas reserves are limited, and it is mainly land-based conventional gas [12,13]. Although China is vigorously developing its unconventional gas industry, the use of shale and tight gas is still limited. However, the fluctuation of international natural gas prices in recent years has made the economic advantages of the development and utilization of unconventional natural gas not obvious. Therefore, conventional natural gas projects are still important basic energy projects in China. This is the reason for choosing conventional natural gas projects as the subject of this paper.

Another subject of this paper is the investment decisions of upstream enterprise. According to the division of the industry chain, a typical natural gas industry can be divided into upstream, midstream, and downstream. The upstream enterprise is mainly involved in the exploration and development of resources. The midstream enterprise involves the construction of natural gas pipelines in industrial and urban areas, natural gas boosters, transmission, and so on. The downstream enterprise involves the reprocessing and utilization of natural gas resources, such as distillation, refining, and processing [14,15].

The upstream activities of conventional gas projects in China are mainly undertaken by large state-owned enterprises, such as China National Petroleum Corporation (CNPC), China Petroleum and Chemical Corporation (SINPEC), and China National Offshore Oil Corporation (CNOOC). In this series of commercial activities, exploration activities are aimed at completing the investigation and evaluation of resources; development activities are aimed at obtaining natural gas resources economically through certain technical means [10].

Generally speaking, investments are made during the exploration and development process. This is the main reason that the economic evaluation and investment management of conventional natural gas projects are worth further study.

However, in the process of economic evaluation of conventional natural gas projects, there are many uncertainties and complicated relations involved. Specifically, these factors can be divided into technical aspects and economic aspects. In terms of technology, such as geological resource endowment and distribution characteristics, natural gas well production declines with regularity, and specific development technology will affect project returns. In terms of economy, macroeconomic environment, structural demand energy, capital source, shareholder composition of corporations, international market price fluctuations, fiscal and tax subsidies, and other factors will affect project returns through different channels and mechanisms. In addition, in these projects, the technical and economic evaluation components are located in different sectors of the enterprise. Their index systems, target functions, and decision-making processes are not identical. As a result, it is difficult for such projects to be economically evaluated in a unified framework, thus making more systematic and scientific decisions.

In order to address these issues, this paper attempts to construct a unified analysis framework. In this framework, technical and economic uncertainties will be included to achieve further unification of these two perspectives. In an attempt to verify the robustness of this framework and simplify the analysis, an independent gas upstream enterprise is introduced, along with several technical and economic uncertainties. The enterprise will conduct technical and economic evaluations of investment plans for a conventional gas project (gas block). In the technical aspect, the economic recoverable reserves of natural gas wells, the initial production capacity, and the declining pattern are the main uncertainties. In the economic aspect, the production costs of gas wells, taxes, depreciation rates, and the market price of natural gas are major uncertainties. In the decision optimization, the enterprise will combine financial net present value, profit, and output into comprehensive consideration. These uncertainties and decision-making processes will be described by a complete set of MATLAB numerical simulation techniques.

Additionally, this framework still maintains an extended interface for in-depth research into technical and economic directions. Based on data availability, the existence of these interfaces enables several technical factors of gas wells to be obtained through more advanced statistical models and techniques. For example, we could use regression analysis, big data and machine learning, and other research tools to analyze the distribution of geological resources, the production, and the decline rate of gas wells. In future studies, the application of all these data and techniques will further refine this framework to make it more comprehensive and accurate.

2. Literature Review

Firstly, this paper will review the existing research literature. These studies focus on the technical and economic uncertainties of natural gas projects.

2.1. Technology

In the technical aspect, the paper mainly reviews the related research of gas well productivity and decline law.

2.1.1. Production Decline Model

The conventional natural gas well decline law is universal. For almost a century, decreasing curves have been used to analyze the production characteristics of conventional gas wells and to predict the production of gas wells, as in the classical model proposed by Arps in 1945 [16]. According to the Arps model, gas well production decline can be divided into three types: hyperbolic decline, exponential decline, and harmonic decline [16].These basic laws and subsequent studies provide a theoretical basis for the resource evaluation and development of oil and gas fields. In addition, many methods have been widely used in conventional oil and gas well production analysis and prediction [17–22]. These methods, a combination of empirical induction and statistical validation, have been used for many years to study the investment and development of natural gas projects. However, these models require more detailed data than the classical Arps models [23–26].

In contrast, during the planning phase of a project, production needs to be estimated more quickly for economic evaluation. Based on this requirement, the Arps model is relatively easy to manipulate. In 1978 and 1982, Sichuan Geological Exploration and Development Research Institute conducted empirical research and analysis on at least 34 gas wells in Sichuan. Most of them obey the exponential decline and hyperbolic decline law [27]. The decline trend of unconventional gas wells is generally obvious, but the exponential decline and hyperbolic decline laws can also be accepted [28]. The decline trend of unconventional gas wells is generally obvious, but exponential decline and hyperbolic decline laws can also be accepted. Due to the limitation of geological conditions, the decline law of each natural gas well is not uniform. More precisely, the pattern of decline between different blocks and gas wells is clearly random.

Scholars have attempted to classify natural gas wells in order to control this stochasticity in theory. However, the stochasticity still exists objectively when the project enters the actual development process. Therefore, it is useful to introduce a production decline model for gas wells into the economic evaluation of the project planning stage. On this basis, the development sequence can be optimized [29].

2.1.2. Gas Well Productivity Classification

Because the productivity of a gas well is affected by many human factors, production pressure differences, gas depth, and productivity stability must be considered when comparing the economics of productivity [30]. Classification according to the average daily stable production of natural gas wells in China: those below 10,000 cubic meters are very low-production wells; those over 100,000 or 300,000 cubic meters are high and extremely high production [31,32]. Based on estimates of productivity and decline law, the economically recoverable natural gas of a well over the entire evaluation period can be referred to as economically recoverable reserves [33,34]. The economic recoverable reserves of natural gas are an important basis for developing the project development plan [35]. For developed gas fields, its economically recoverable reserves are equal to the sum of current cumulative gas production and remaining economically recoverable reserves.

Therefore, the production forecast and risk assessment of the project can be carried out by combining the declining production model of the gas well with the classified production capacity. The economic recoverable reserves can be used to assess the remaining economic recoverable reserves of a gas well. In particular, this metric is commonly used in natural gas projects in China when the residual production depreciation method has been used to measure the depreciation rate of a gas well. This will be explained in detail in the model.

2.2. Economic

There are multiple sources of economic risk for natural gas projects. According to the project financial plan and cash flow statement, cash inflows include investment and financing funds, operating income, subsidies, and so on. Cash outflows include, but are not limited to, long-term and short-term borrowings or credit facilities, interest expense, operating costs, and tax expense. Geological and technical risks will cause the actual recovered resources of the project to differ from the planned recovered resources [36]. The risk of the construction process will affect the project's investment cost [37]. Policy risk will exogenously affect project revenue, such as affecting the value of tax rates, interest rates, and benchmark yields [38,39]. The mechanisms of industry and macroeconomic impacts are more complex. This is because China is highly dependent on international imports for its natural gas supply [40], while the use of renewable energy remains limited [41]. Therefore, it remains important to obtain as much of the proven gas resource as fast as possible [42]. This is also the main decision objective of large state-owned oil and gas companies.

It is noted that scholars have been gradually incorporating technical and economic factors into the ecological and economic assessment of natural gas projects. However, these analyses that consider the micro-level usually require sufficient data. For example, industrial neural network (ANN) modeling strategies and least square support vector machine (LSSVM) methods have worked well for predicting natural gas well decline curves based on sufficient data [18]. By applying these methods, scholars can more effectively estimate production, decline rates, and recovery rates for natural gas projects [43,44]. Fixed and variable costs of natural gas projects can also be more accurately estimated [45,46].

Another proven technical approach is the use of a combination of empirical data and simulation. For example, simulation methods are used to describe the uncertainty of natural gas project reserves and their investment and optimization [47,48]. Some financial index could be introduced for measuring the urgency and economics of a project, such as NPV and DCF [36,49,50]. Based on this technique, it is also feasible to introduce multiple risk factors and a value-at-risk approach to measure project risk [51].

2.3. Brief Summary

To sum up, the review shows that many scholars have analyzed the economic impact of geological structures and resource endowments on these projects from a technical perspective. Some scholars have also progressively linked economic factors such as cost, price, and cash flow to technical evaluation results. This suggests that it is feasible and meaningful to integrate a research framework of technical and economic perspectives.

Within this framework, the robustness can be more fully verified by introducing the management, decision-making, and optimization behavior of upstream enterprises. Since enterprises are the core entities of interest in the meso-economy, their decisions will have a significant impact on the society and the economy. Their decisions need to consider not only financial returns, but also their growth strategy, business status, and social responsibility. To this end, in the next chapter, we will establish a model that integrates technical and economic uncertainties, and a numerical simulation will be used to illustrate the decision making and optimization behavior of an enterprise.

3. The Model

3.1. Environment

This paper first establishes an environment based on the micro production unit (i.e., gas well). In this environment, time is discrete. The days, months, and years could be introduced as basic periods. The economic evaluation of the project will be carried out during a full evaluation period. We first assume some key technological and economic uncertainties, and represent the information set and decision of the enterprise as follows. The reasons for these settings will be further explained later.

1. Technical risk shock

Gas wells are heterogeneous. The heterogeneity is mainly manifested in the differences in economic recoverable reserves, initial production capacity, and parameters in the decline model.

The parameters of the production and decline models are estimable. The Arps model will be used to estimate the production and decline characteristics of gas wells due to its tractability. Of course, the parameters in the model satisfy specific distribution characteristics, such as uniform distribution.

A conventional natural gas well has a theoretical stable production period. During this period, the well will maintain a theoretically constant production rate through technical measures such as pressure and flow rate control. This constant production is also referred to as the initial production in the Arps model.

2. Economic risk shock

Variable costs consist of unit operating costs and period expenses. The operating costs are directly related to the production of natural gas, such as material purchases, labor, electricity, vehicles, and so on. Let the unit operating costs be equal to the mean value of all operating costs. The period expenses include: selling expenses, administrative expenses, financing interest. Since these costs are not directly related to the production of natural gas, they are not considered in this paper.

Fixed costs are the initial investment in each gas well and are expressed as capital funds in the financial statements. When these are financed from the company's own funds, there is no need to consider interest on financing.

The residual production depreciation method is used to calculate the depreciation of gas wells. Because this depreciation method can effectively reflect the remaining economic recoverable reserves of gas wells, it is widely used in the economic evaluation of conventional natural gas projects in China.

All taxes are introduced as a comprehensive, fixed percentage. This includes, but is not limited to, value-added tax and additional taxes such as urban construction tax and education fees.

Natural gas prices satisfy the random walk, and there are spillover effects in the international natural gas market. This is used to fully characterize the impact of the international market on domestic natural gas projects in China.

3. Enterprise decision optimization

The enterprise will optimize the investment decision according to different decision objectives and considering the risk impact of technology and economy. The specific mechanism is as follows:

Based on the results of the technology assessment, the enterprise determines the evaluation period, develops a production program, and determines the average variable costs and taxes under a fixed percentage.

The enterprise can decide the quantity of gas wells to be put into production in period 1, and the time interval for the remaining gas wells in the progressive production. These are defined as the lag periods (i.e., x) and the initial capacity (i.e., y). In particular, the enterprise will prioritize the development of gas wells with higher evaluated production because these gas wells are more investable in practice. In this paper, three optimization objectives are considered as follows:

(a) The project will achieve maximum financial gain.
(b) The project will achieve an optimal balance between financial income and net profit.
(c) The project will achieve an optimal balance between financial returns and production.

We describe the information set and decision process in Figure 1.

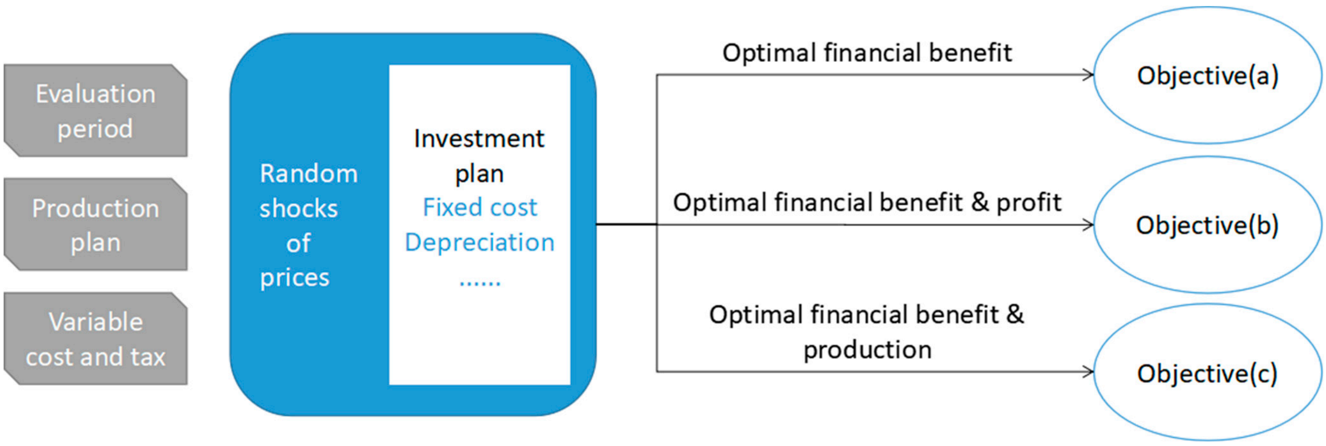

Figure 1. Information set and decision process.

3.2. Economic Evaluation Model

For a block with I gas wells present, the serial numbers of all gas wells expected to be put into production are denoted by the superscript i. If the entire evaluation period is denoted as T, the subscript t represents a specific period. Throughout this paper, the periods are denoted by months.

3.2.1. Economic Evaluation Model of Gas Well

1. Economically recoverable reserve of gas well

During the exploration phase, technical estimates of economically recoverable reserves are made for each gas well. The economically recoverable reserves of each gas well are expressed as:

$$\overline{q}^i \in \mathbb{R}^+ \tag{1}$$

where:

$i \in [1, I]$ is the serial number of gas wells, I is the total number of gas wells;

$\overline{q}^i$ is the economically recoverable reserve of gas well i, 10^4 m^3. Please notice that we do not introduce a time index for it, since it is a stationary value.

2. Production decline model of gas well

The production of gas well i at period t is expressed in the Arps model as follows [16,25,52]:

$$q_t^i = q_0^i\left(1 + D_0^i n^i t\right)^{-1/n^i} \tag{2}$$

$t \in \left(s^i, T\right]$ is the time index of decline production period, month;
s^i is the stable production period of gas well i, month;
q_0^i is the production of gas well i at the stable production period, and it also be calculated as initial production at the beginning of decline production period, m^3;
q_t^i is the production of gas well i at period t, m^3;
D_0^i is the initial decline rate of gas well i, %;
n^i is decline exponent of gas well i, %. If the decline exponent $n \in (0,1)$, the equation of hyperbolic decline is $q = q_0(1 + D_0 nt)^{-1/n}$.

3. Variable cost of gas well

Based on the setting of the environment, the variable cost can be represented simply as follows:

$$c_t^i = \alpha^i q_t^i \tag{3}$$

where:
c_t^i is the variable cost of gas well i at period t, CNY;
α^i is the unit variable cost of this block, CNY per m^3.

4. Fixed cost of gas wells

The fixed cost of a gas well varies depending on various technical risks. Based on actual project experience, the fixed cost of a gas well can generally be abstracted by two parts: (a) The fixed part, which can usually be estimated prior to investment in conjunction with geological features, and the fixed costs of gas wells within this block are roughly equivalent; and (b) the non-fixed part, which is subject to random shocks of heterogeneity in the actual investment. We denote it as:

$$f_1^i = \overline{f}_a + f_b^i \tag{4}$$

where:
f_1^i is the fixed cost of gas well i at its first period, CNY;
$\overline{f}_a$ is the average of the fixed cost (a) of all gas wells, CNY;
f_b^i is the random value of fixed cost (b) of gas well i, CNY;

5. Depreciation of gas well

Because not every gas well's economically recoverable reserve can be completely exploited, the depreciation rate for gas well i at period t is expressed by residual production method as:

$$\delta_t^i = \frac{\left(\overline{q}^i - \sum_{t_1^i}^{t} q_t^i\right)}{\overline{q}^i} \tag{5}$$

where:
δ_t^i is the depreciation rate of gas well i at period t, %;
$t \in [1, T]$ is the time index for whole period, month;
$\overline{q}^i$ is the economically recoverable reserve of gas well i, combine with Formula (1);
t_1^i is the first month of operation of gas well i;
$\sum_{t_1^i}^{t} q_t^i$ is the accumulated production of gas well i from the first month of operation to period t.

In this paper, we do not consider the impact factors such as liquidation cost, salvage value, and amortization, but these can be introduced into the model and do not have an essential effect on the main research results. For simplicity, we denote the depreciation of gas well i in period t as follows.

$$d_t^i = f_1^i \cdot \delta_t^i \tag{6}$$

where:

d_t^i is the depreciation of gas well i at period t.

3.2.2. Natural Gas Price Forecast Model

Brownian motion and mean regression models are commonly used to describe stochastic price fluctuations in financial markets and energy commodity markets [53–56]. A typical model considering geometric Brownian motion and mean-reverting processes is as follows:

$$p_t = p_{t-1} + K(\overline{p} - p_{t-1})dt + \sigma p_{t-1}\sqrt{dt}\varepsilon \tag{7}$$

where:

$\overline{p}$ is the equilibrium price of natural gas, CNY per m^3;
p_t, p_{t-1} are the price at period t and its previous period, CNY per m^3;
p_0 is the actual ex-factory price at the initial period, CNY per m^3;
K is the reversion rate. If it is 0, then the process is not mean reversion, but Brownian motion.
dt is the time interval;
σ is the volatility of prices;
ε is the random error.

3.2.3. Economic Evaluation Model of Gas Block

1. Production, cost and depreciation

The production, variable cost, fixed cost, and depreciation of the block as follows:

$$Q_t = \sum_i^I q_t^i \tag{8}$$

$$C_t = \sum_i^I c_t^i \tag{9}$$

$$F_t = \sum_i^I f_t^i \tag{10}$$

$$D_t = \sum_i^I d_t^i \tag{11}$$

2. Price and tax

In this paper, all taxes are represented as comprehensive taxes. The tax inclusive price of natural gas is expressed as:

$$P_t = \hat{P}_t(1 - \tau) \tag{12}$$

where:

τ is the comprehensive tax rate of natural gas, %;
P_t is the price including tax per cubic meter natural gas at period t, CNY;
$\hat{P}_t$ is the price not including tax per cubic meter natural gas at period t, CNY;

3. Income and profit

Based on the above analysis model of the gas well and block, the revenue and profit function of the block can be established. Since the assumption of corporate financing process is relaxed, we can focus on the analysis of the block's earnings before interest after tax (EBIAT). Combining Equations (8), (9) and (11), the following can be obtained:

$$\prod_t = P_t Q_t - C_t Q_t - D_t \tag{13}$$

where:

$\prod_t$ is the net profit or EBIAT of block at period t, CNY;
$P_t Q_t$ also represented the net cash inflow of block at period t, CNY;
$C_t Q_t + D_t$ represent, correspondingly, the net cash outflow of block at period t, CNY;

4. Financial net present value

From Equation (12), the financial net present value (FNPV) of this block can be expressed as follows:

$$FNPV = \sum_{t=1}^{T} (P_t Q_t - C_t Q_t - D_t)(1 - i_c)^{-t} \tag{14}$$

where:

$\sum_{t=1}^{T} (P_t Q_t - C_t Q_t - D_t)$. is the accumulated net cash flow of block from period 1 to T, CNY;
i_c is the standard discount rate, %. In China, the benchmark yield is chosen as the standard discount rate in almost all gas and oil economic evaluation cases.

4. Simulation Result and Discussion

As this paper focuses on adopting a new analytical approach to reconcile technology with economics, and due to the commercial confidentiality of production and financial data of oil and gas field companies, actual production data are not used in this paper due to data availability. Nonetheless, we still obtained key parameters and distribution characteristics through in-depth interviews with corporate technicians and economic assessors. In this chapter, we will first build the simulation model and illustrate the optimization results for the three objectives. Model parameters are shown in Tables 1 and 2.

4.1. Setting

4.1.1. Economic Evaluation Model

1. Literature Calibration

According to the production grade of the gas well, the initial production of the gas well in the stable production period is between one and eight [31]. This is because project teams typically do not develop gas blocks with very low production rates, and the probability of an extremely high production gas well is low as well. Combined with the above analysis, the probability of occurrence of the interval one to eight is relatively high.

The empirical study of Sichuan natural gas projects reflect that most gas wells obey exponential and hyperbolic decline laws. The initial decline rate of gas wells is usually between 0.005 and 0.03, and the decline exponent is usually between 0.01 and 1 [27]. Unconventional gas wells also obey these decline laws; their initial decline rate is higher and their decline exponent is lower, indicating that these gas wells decline faster. Meanwhile, the initial decline rate and decline exponent also typically fall within the above range [28,57].

According to the opinions of the expert group, the values of other parameters are determined in this paper. For example, in the economic evaluation of some natural gas projects, the price of natural gas, including tax, is usually 1.3 CNY/m^3. Although variable costs vary per well, the total value ranges from 0.1 to 0.7 CNY/m^3. Under this capacity setting, the investment per well during the construction period is between CNY 60 million and CNY 120 million, of which the investment part that can be estimated relatively accurately is generally CNY 80 million. This is also the fixed part considered in the model. At the same time, the vast majority of conventional gas wells have stable production periods of roughly 1 to 5 years, followed by periods of decline.

2. Parameter setting

Table 1. Parameter list of economic evaluation model.

Symbols	Value	Description
T	300	total months for 25 years, month
	27	workdays
I	30	total number of gas wells
q_0^i	(1, 8)	the mean economically recoverable reserve of all wells, 10^4 m^3
s^i	(36, 84)	the mean stable production period of all wells, month
D^i	(0.005, 0.03)	initial decline rate in Arps model
n^i	(0, 1)	decline exponent in Arps model
α^i	(0.1, 0.7)	unit variable cost of this block, CNY per m^3
f_1^i	(0.5, 1.2)	mean definite fixed cost for all wells, CNY 10^8
τ	0.17	composite tax rate of natural gas, %
i_c	0.08	standard discount rate, %

Table 2. Parameter list of natural gas price forecast model.

Symbols	Value	Description
$\overline{p}$	(1, 2)	expected equilibrium price
p_0	1.2	actual ex-factory price
K	0	Brownian motion
dt	1/12	time interval, per month
ε	N (0, 1)	normalization

Although these random factors may have specific distribution characteristics, let all these random variables satisfy a uniform distribution in order to focus more on the study in this paper. In particular, different distribution characteristics, although leading to different results, do not change the results of this model.

4.1.2. Decision Optimizing

In the environment of the model and Figure 1, the enterprise can optimize the decision by adjusting indicators y and x. For example, if y takes a larger value and x is smaller, this indicates that more gas wells would be developed at period 1 and that the remaining wells would be developed at shorter intervals. This allows the project to recover resources more quickly. When prices are constant or increase, higher revenues and FNPV can be achieved in the short term. However, in the mid-stage or late-stage, this strategy will leave the project with no more new wells to exploit. That also will leave the old wells, that have been exploited for many years, facing the obvious effects of the natural decline law. If prices do not remain the same and increase as expected after a few years, but instead decline, this would make the investment risk of the project even higher.

This is clearly an aggressive but risky investment strategy. The other conservative investment strategy is to lower y and raise x, while keeping the project as valuable as possible (e.g., positive FNPV). In this way, the project may have a longer life cycle and be more sustainable. Of course, when prices rise in the short term, this strategy makes it difficult to obtain a higher financial return and larger production for the overall project.

More specifically, combined with Figure 1, we represent these objectives as follows.

(a) Positive FNPV, which is the largest among all scenarios.
(b) Positive FNPV, and the net profit is greater than and closest to the average of all scenarios.
(c) Positive FNPV, with yield greater than and closest to the average of all scenarios.

Under the influence of geological features and prices, the investment plan of the project is different in order to achieve the above three decision-making objectives. Figure 2 briefly represents the possible investment choices under these decision objectives.

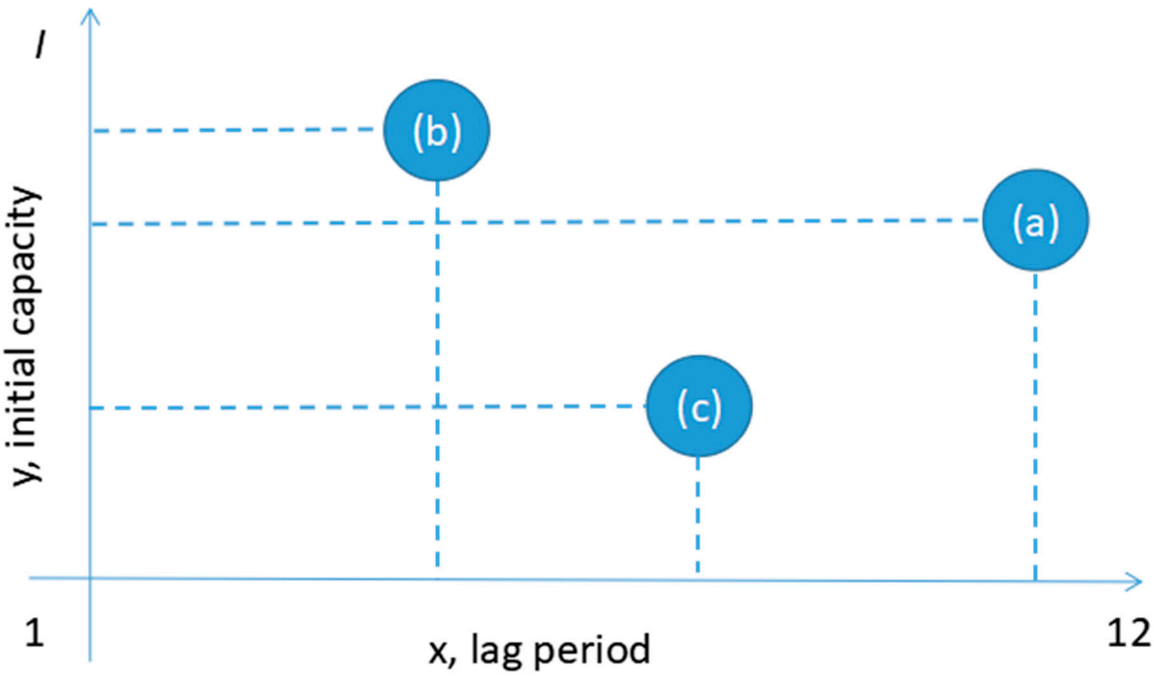

Figure 2. Optimizing objectives.

In this graph, the vertical axis represents the number of gas wells at period 1. The horizontal axis represents the number of remaining unexploited gas wells. The points in the graph represent the combination of decisions used to achieve specific objective. Of course, when technical and economic uncertainties are introduced, the initial capacity, declining curve of the gas wells, and the gas price will all vary. This will allow for a rich variety of decision combinations. In the subsequent sections, this paper will illustrate these issues more directly with numerical simulations.

4.2. Result and Disscusion

4.2.1. Production Plan

1. Initial Production

As in Formula (2), q_0^i is the production of gas well i at the stable production period, as well as the initial production in the Arps model. Combined with the simulation settings, we performed 1000 simulations and presented them in the form of boxes. We report the simulation result for it in Figure 3. Based on the simulation settings, the 1000 simulations result is reported in Figure 3.

In the Figure 3, each box represents the potential stable production of this gas well. On each box, the center line represents the median productivity of that gas well. The top edge represents the 25% quantile case. The bottom edge indicates the case of the 75% quantile. The top and bottom edges of the dotted line indicate the maximum and minimum productivity of the gas well, respectively.

Combined with the above analysis, it can be seen that the gas wells with higher productivity will be put into production in the early stage. Later gas wells have less productivity. This is in line with the general law of natural gas project production. However, the production capacity of gas wells still fluctuates from period to period due to the uncertain influence of geological conditions.

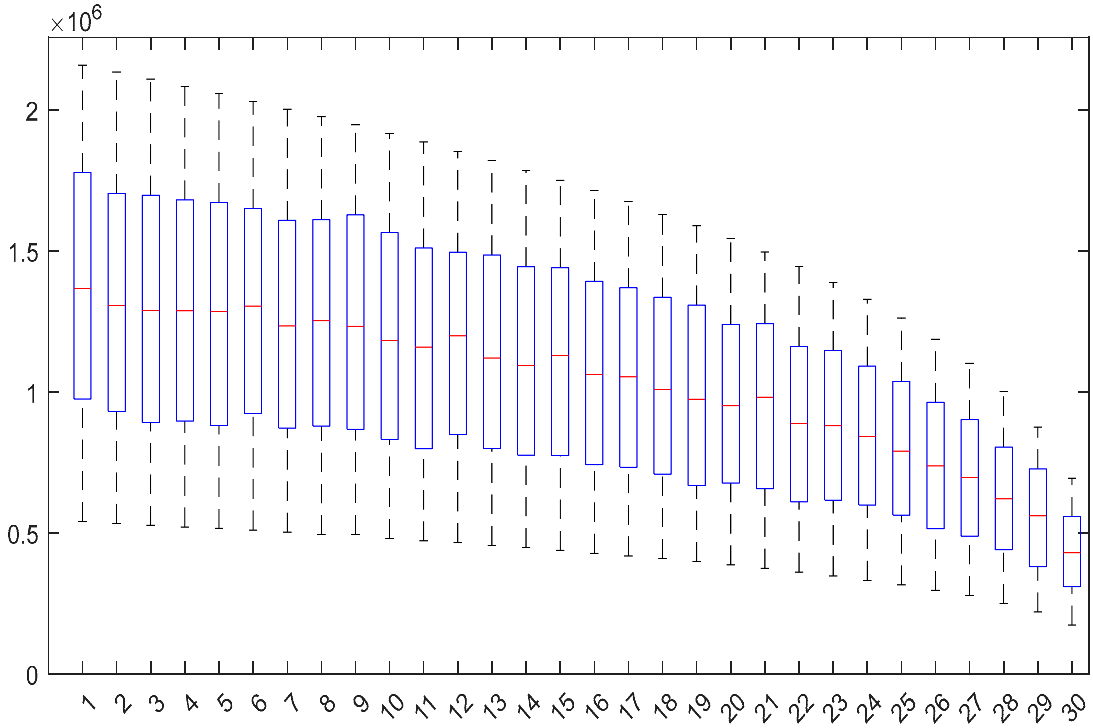

Figure 3. Initial and stable production of gas wells.

2. Single well production decline simulation considering stable production period

Next, uncertainties such as evaluation period, initial yield, stable production period, and decreasing model are introduced. After conducting 1000 simulations, four project scenarios were selected for this paper. This is to adequately compare the impact mechanisms of these uncertainties. Among them, projects 1 and 2 were randomly selected. In project 3, the situation in the 80% quantile of all results was selected to describe the situation with ideal productivity. Project 4 selected the mean case among all the results to characterize the mean case of the results. These results are reported in Figure 4, Figure 5, Figure 6, and Figure 7, respectively.

In these plots, the horizontal axis represents the evaluation period, and the vertical axis represents the production of gas wells during that period. These plots reflect some differences in the initial and stable production and decreasing production of gas wells. Combined with the assumptions in environment and Figure 3, these plots visually present the following patterns. First, gas wells with smaller numbers have higher initial yields, while gas wells with larger numbers have lower initial yields. Second, there will still be fluctuations and randomness in the initial production and decreasing rate of gas wells.

Although projects 1 and 2 were generated randomly, the overall production of project 1 is higher than that of project 2. Projects 3 and 4 reflect the ideal case and the average case of all results. In particular, projects 3 and 4 also more intuitively illustrate the production characteristics of the gas wells during the stable production periods and decline production periods.

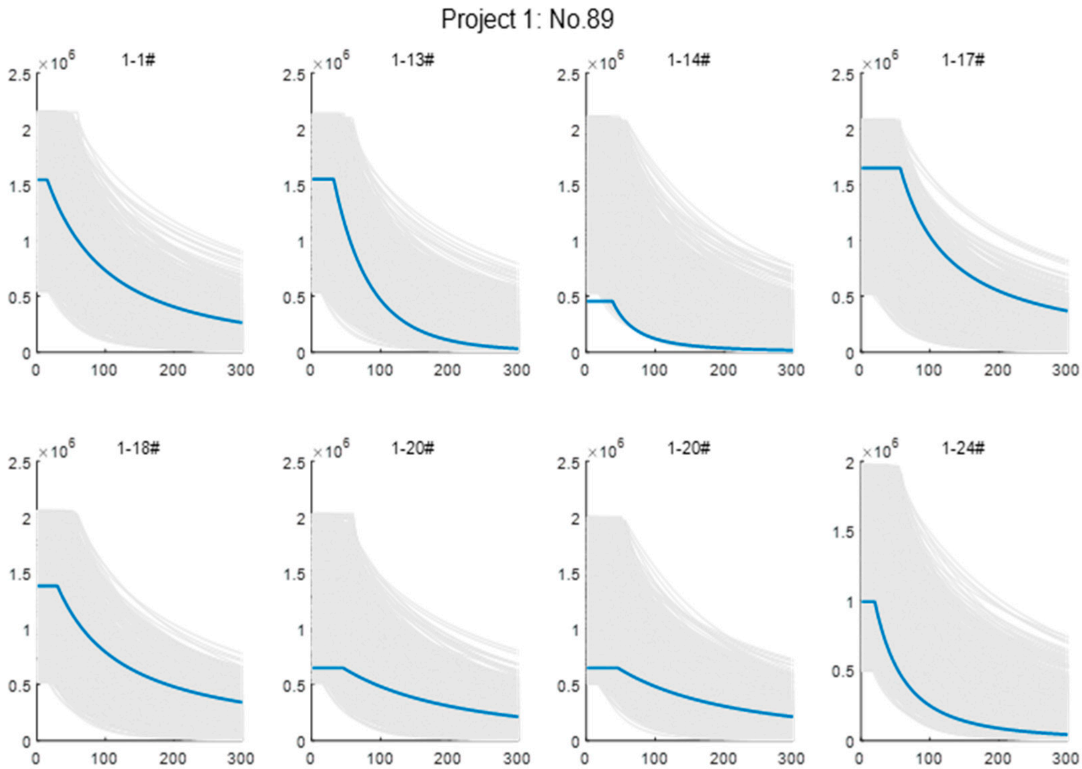

Figure 4. Production plan of project 1.

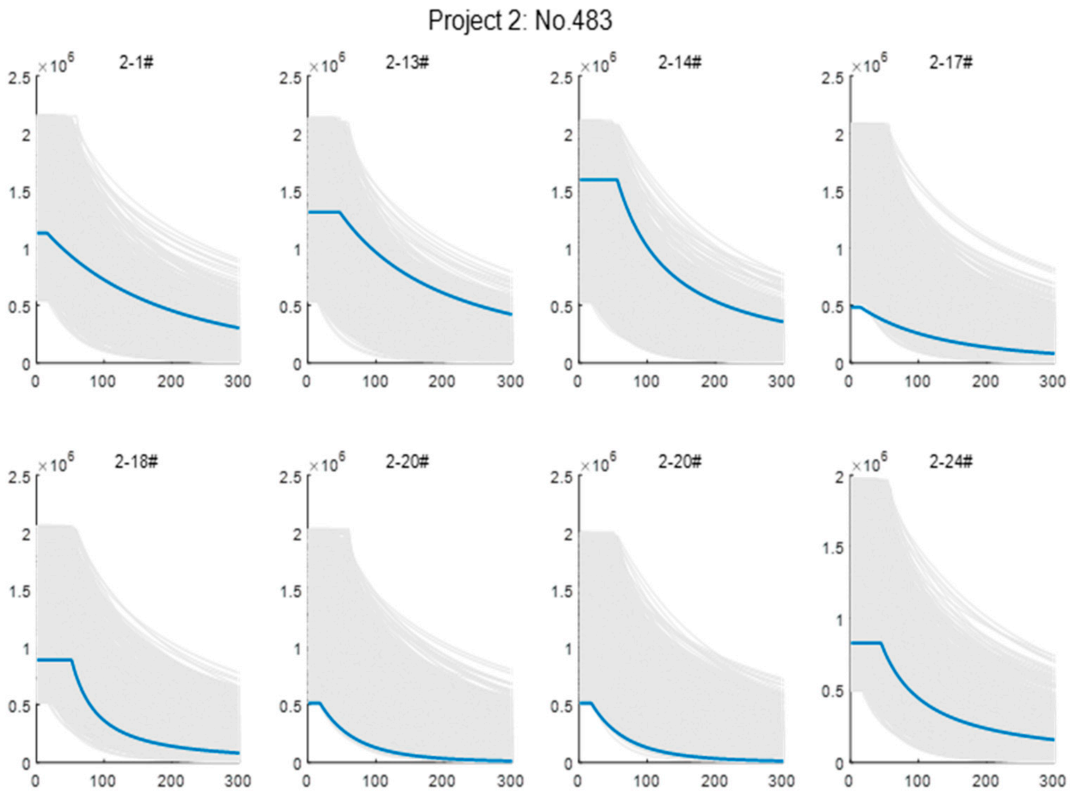

Figure 5. Production plan of project 2.

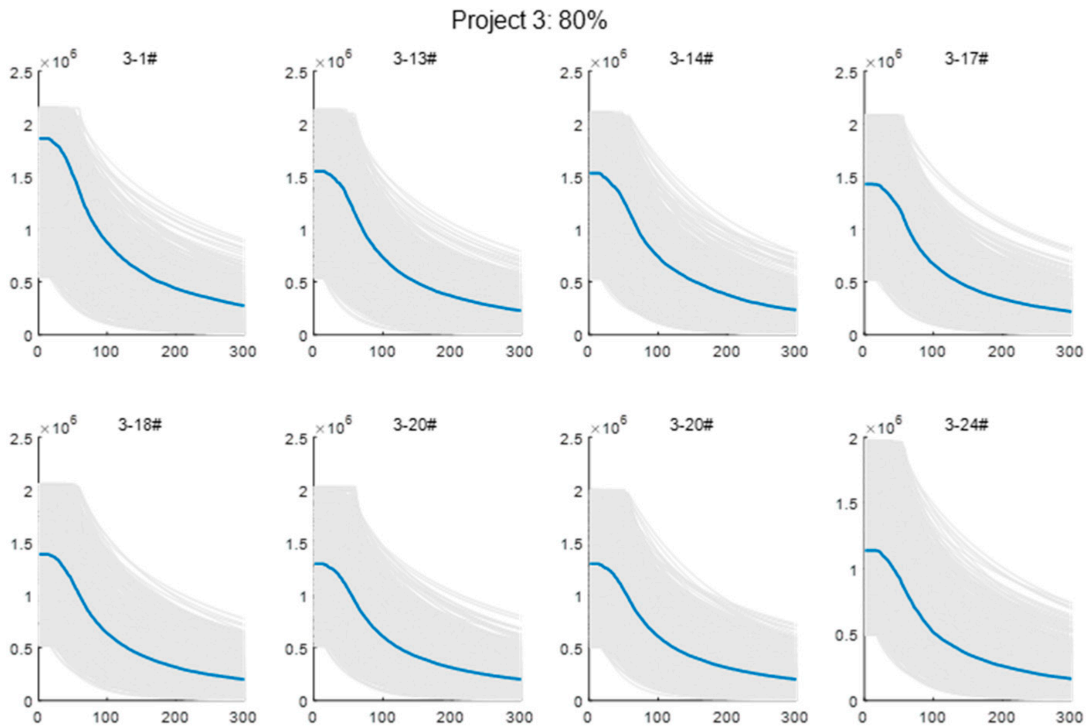

Figure 6. Production plan of project 3.

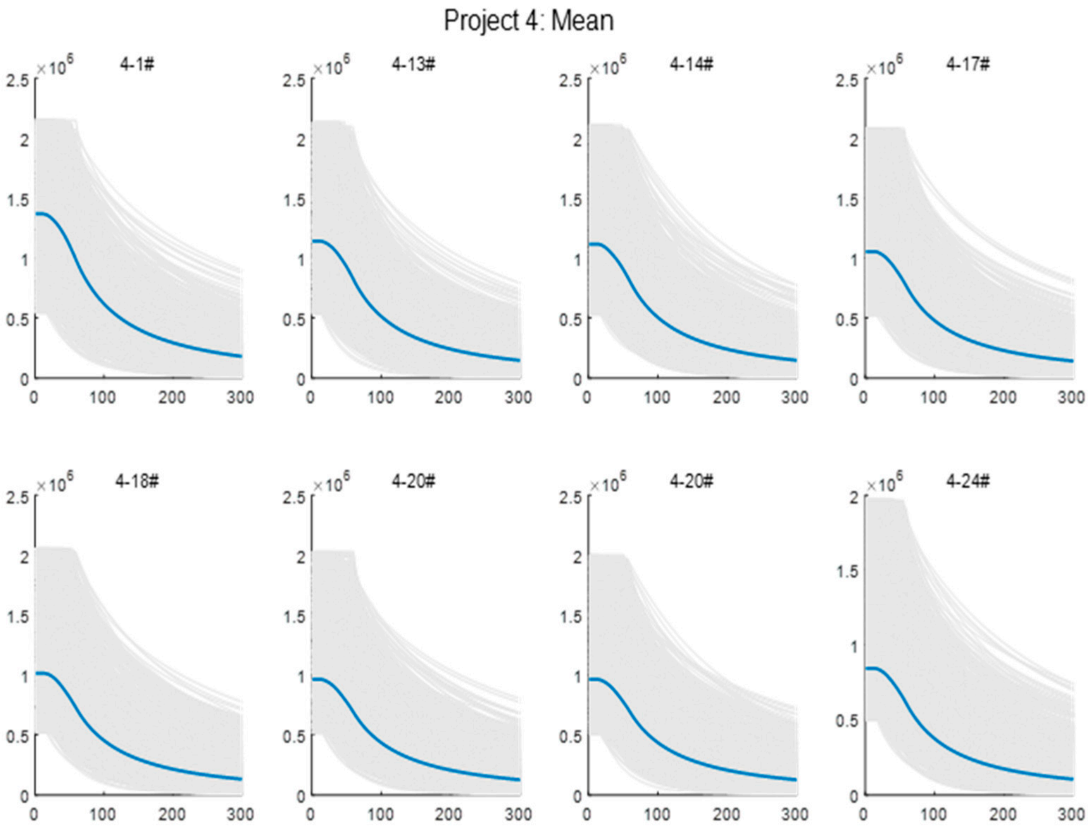

Figure 7. Production plan of project 4.

4.2.2. The Evaluation of Investment Plan

1. Scenarios of Gas Prices

Since there are constant, decreasing, and increasing long-term mean values of natural gas prices, the 1000 times random walk simulation for gas price scenarios are reported in Figures 8–10.

Figures 8–10 reflect the fluctuation of natural gas prices around a constant mean value and with the clear downward or upward trend during 300 periods.

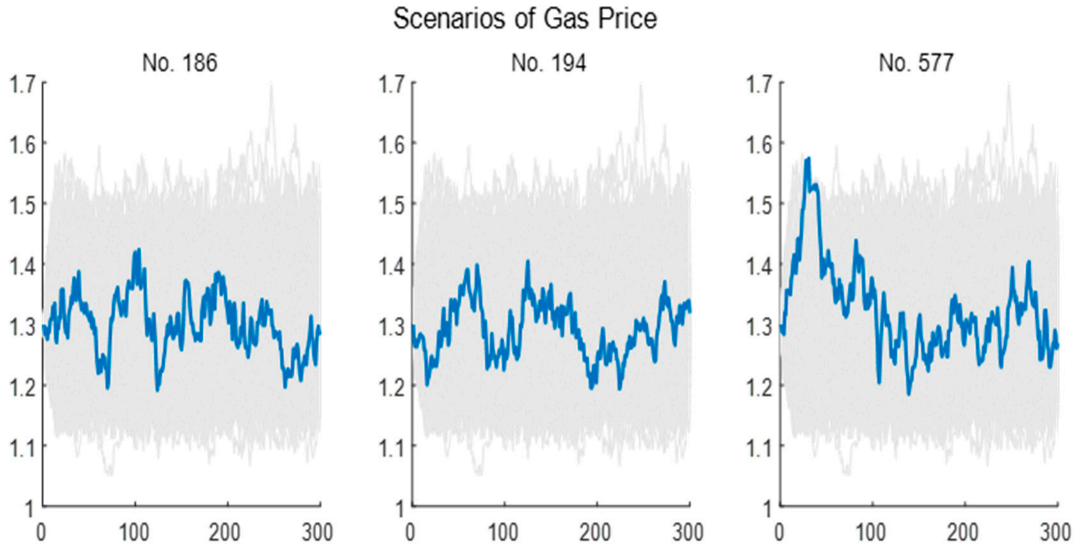

Figure 8. Constant mean value scenarios of gas prices.

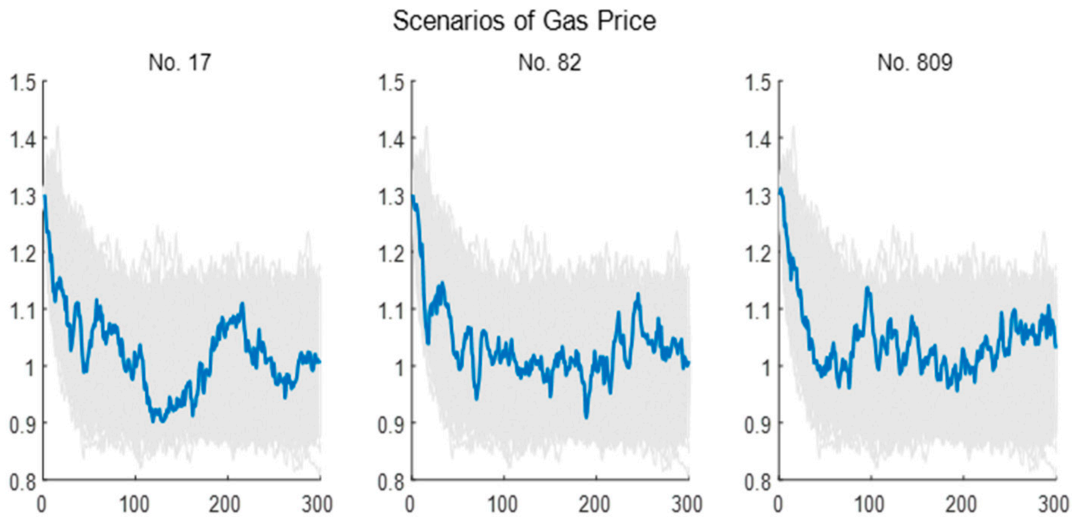

Figure 9. Mean value decline scenarios of gas prices.

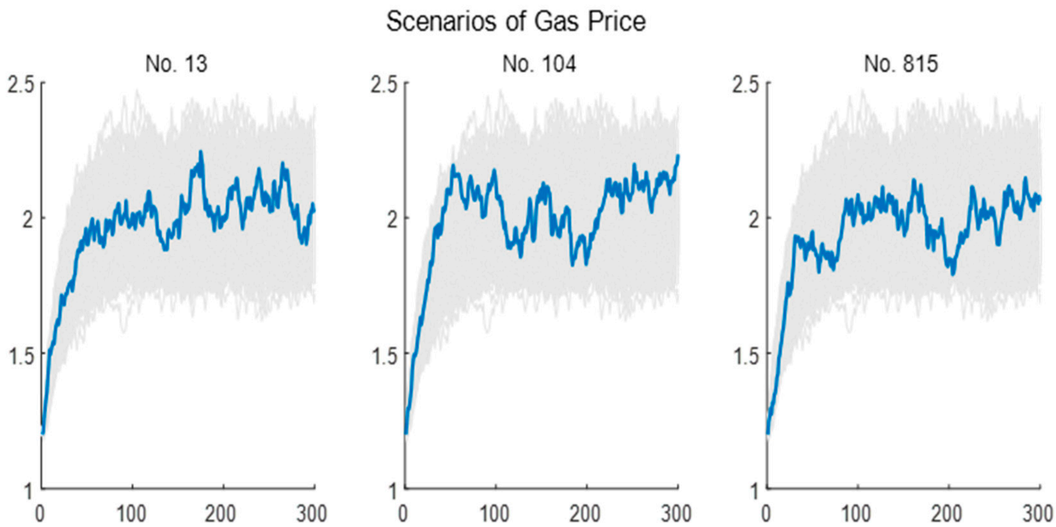

Figure 10. Mean value increase scenarios of gas prices.

2. Static analysis

Using these figures below, a static analysis of the investment decision scenarios is performed. First, a price scenario with constant long-term mean is randomly selected, as shown in Figure 11.

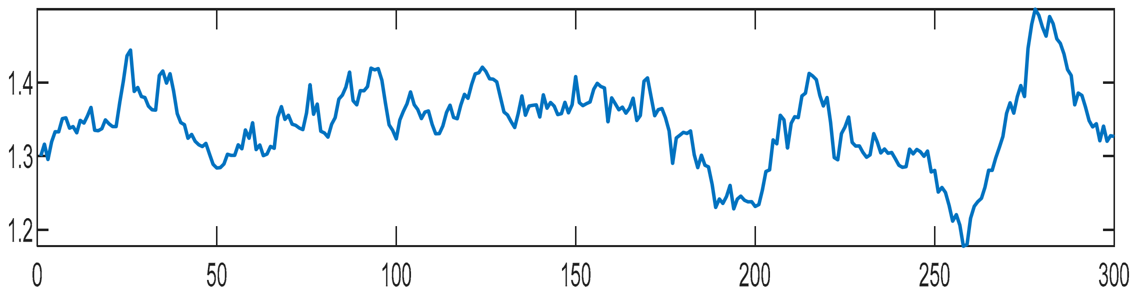

Figure 11. Selected constant mean value scenario of gas prices.

Second, an investment scenario is chosen. In this scenario, the lag period is 4 (i.e., x = 6) and initial capacity is 6 (i.e., y = 4), which is represented as (6,4) in the title of figure. Finally, two randomly generated items, item 1 and item 2, are selected for analysis, as shown in Figures 12 and 13.

In these figures, the left subgraph shows the production per period of the project. The middle subgraph shows after-tax income, and operating costs including variable costs, and the depreciation of fixed assets. The right subgraph shows net profit per period, which is the after-tax revenue minus operating costs per period, and the dotted line in this subgraph shows the case where net profit equals zero. The discussion of project 3 and project 4 is placed in Appendix A, as shown in Figures A1 and A2.

The left subgraph of Figure 12 reflects that under this investment plan, the output of Project 1 will increase gradually at first. This is because as the gas wells are gradually exploited, the production of each well is not affected by a significant decline effect. Around the 100th period, when all gas wells are in production, there will be a gradual and more significant decline in project production. As shown in the middle subgraph, this pattern will also significantly affect after-tax income and total cost. Depreciation is higher until the 100th period due to the use of the residual production depreciation method. This makes after-tax income and total cost show a pattern of gradual increase, but rapid decrease. As shown in the right subgraph, the net profit of the project shows a similar trend when the long-term price is constant at its mean value.

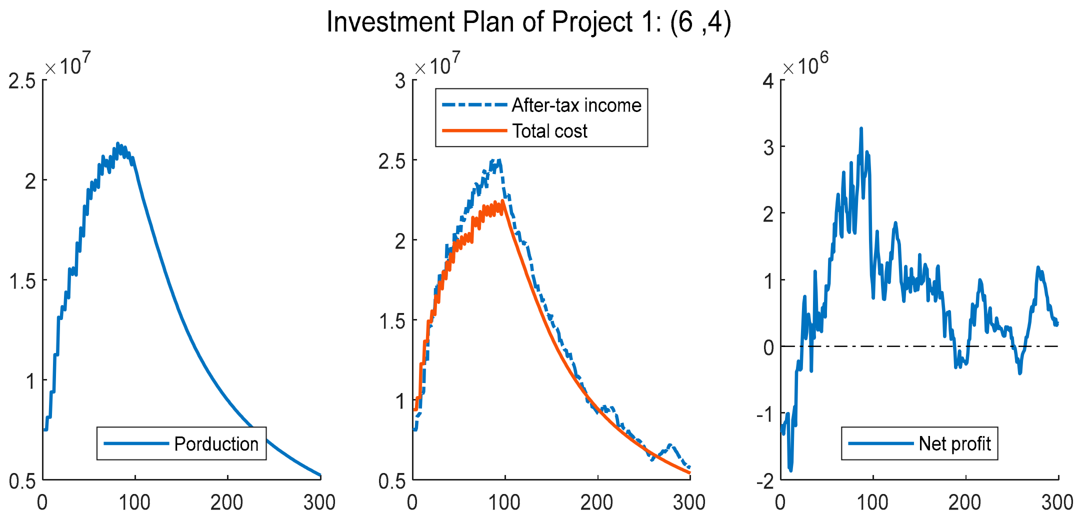

Figure 12. Production, income, cost and, net profit of project 1.

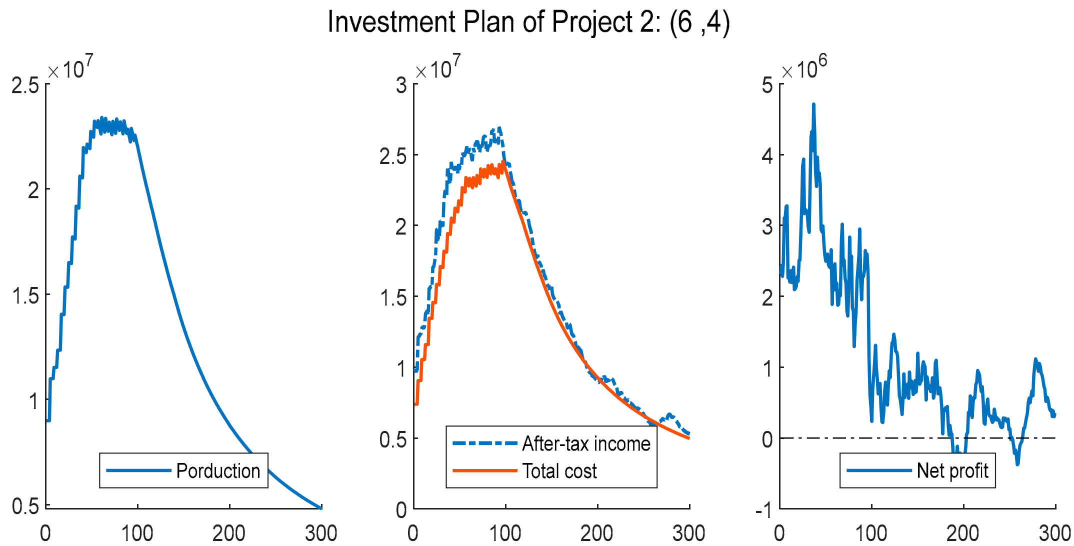

Figure 13. Production, income, cost and, net profit of project 2.

However, it is worth mentioning that the prices shown in Figure 11 will rise around the 250th period. The net profit of project 1 will increase significantly in this period. Note that this is the end of the project's life and production is already low, but the increase in net profit is significant. The reason for this is that the depreciation of the project is already very low at this point. This also reflects the fact that, in similar price scenarios, there still seems to be a better investment for some older gas wells with very significant production declines.

Project 2 generally shows a similar pattern to Project 1. Compared with Project 1, the left subgraph of Figure 13 reflects that since the production of Project 2 is higher, the impact of the decline effect is lower, and the production and stable production periods are longer. This allows Project 2 to maintain a relatively stable high yield from about the 80th to the 150th period. The right-hand subplot of Figure 13 reflects that Project 2 generates greater net profits in each period. Moreover, for the same price scenario, Project 2 makes better investment sense in its later periods. Although its net profit does not increase to the same extent as Project 1, its overall production is larger.

4.2.3. Optimizing

Now, the decision optimization behavior of the enterprise is introduced. In the environment of the model, as well as in Figure 2, the three decision objectives of the firm are defined as (a), (b), and (c). This section will continue the discussion for the four items selected in Section 4.2.1. In addition, this section will focus on two scenarios of long-term mean value of natural gas prices: constant and increase. They are reported in Figures 14–23.

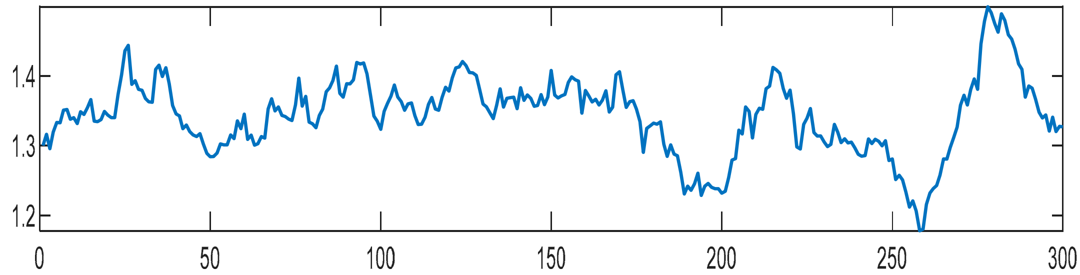

Figure 14. Selected constant mean value scenario of gas prices.

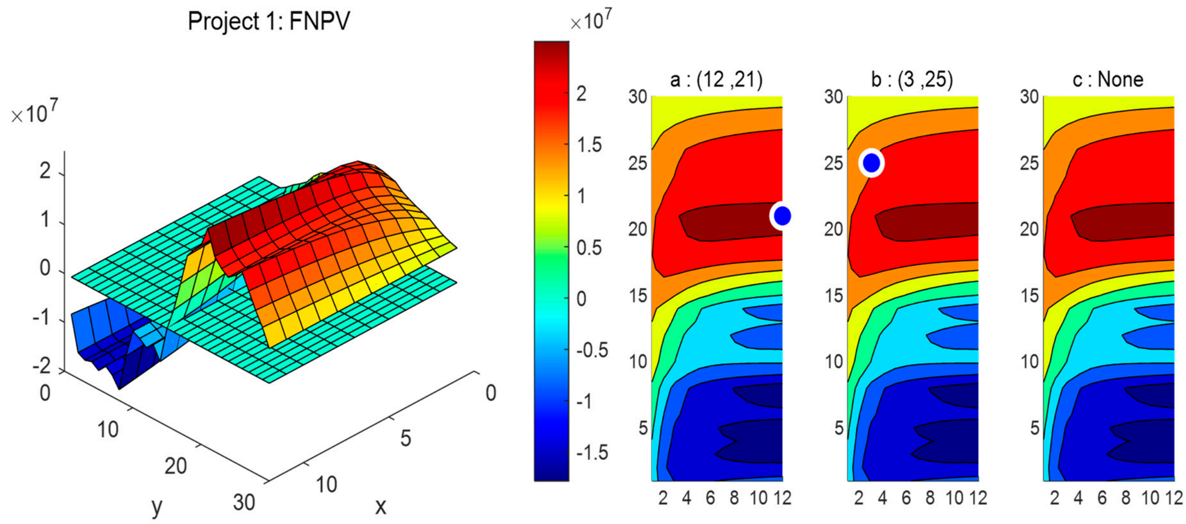

Figure 15. Decision-making for project 1.

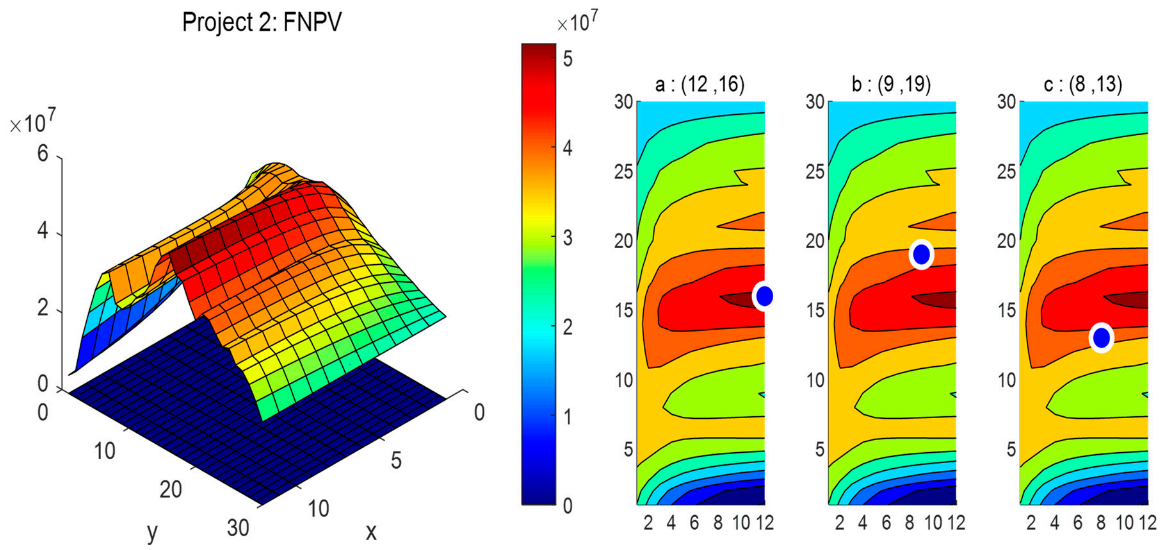

Figure 16. Decision-making for project 2.

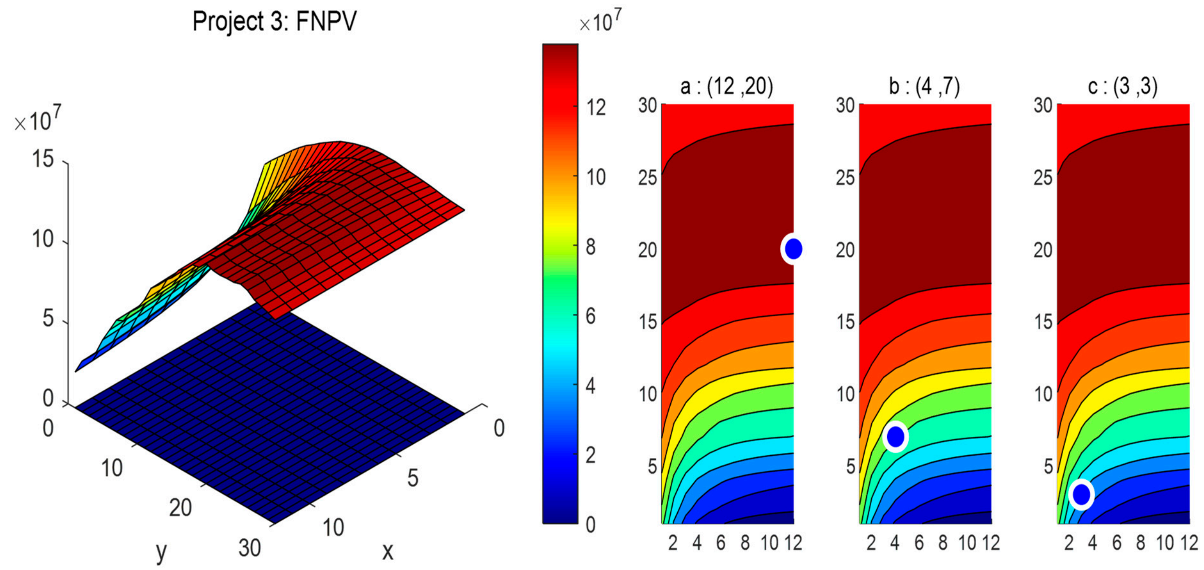

Figure 17. Decision-making for project 3.

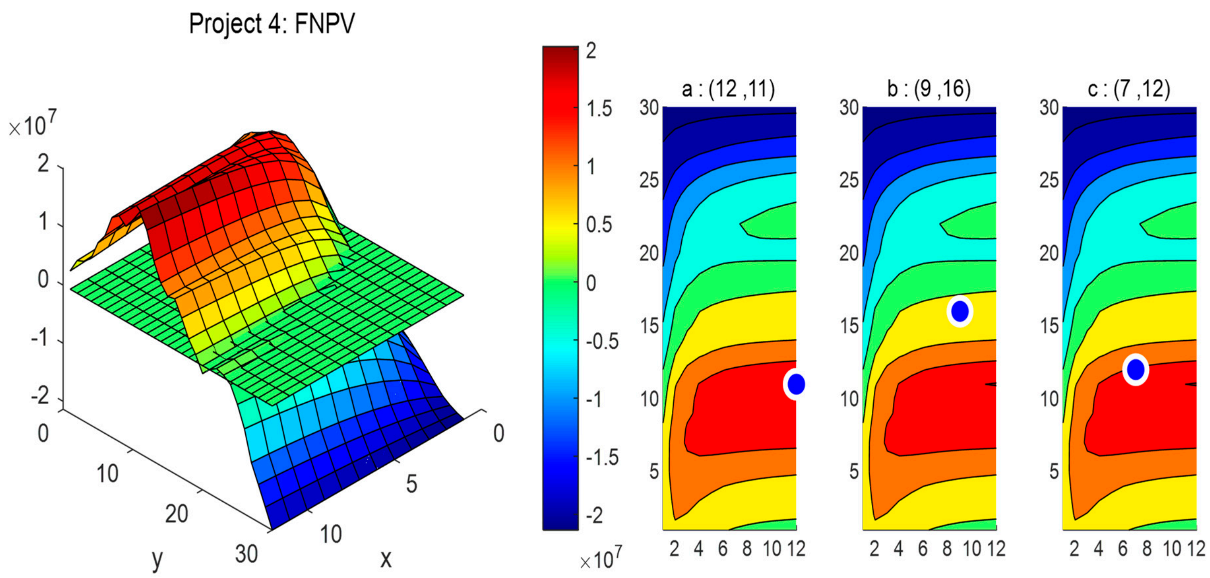

Figure 18. Decision-making for project 4.

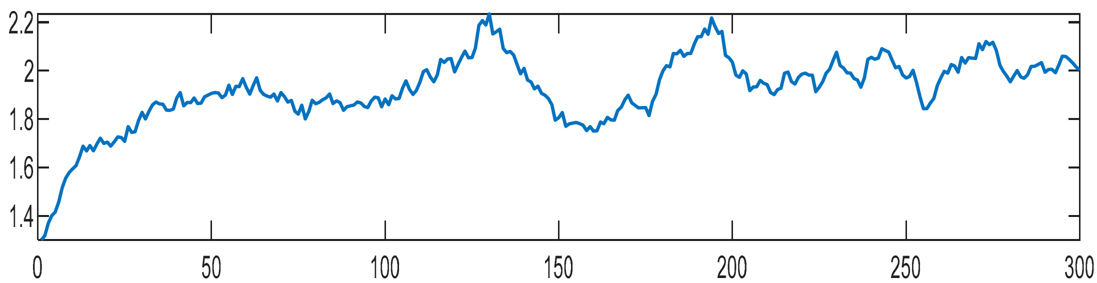

Figure 19. Selected mean value increase scenario of gas prices.

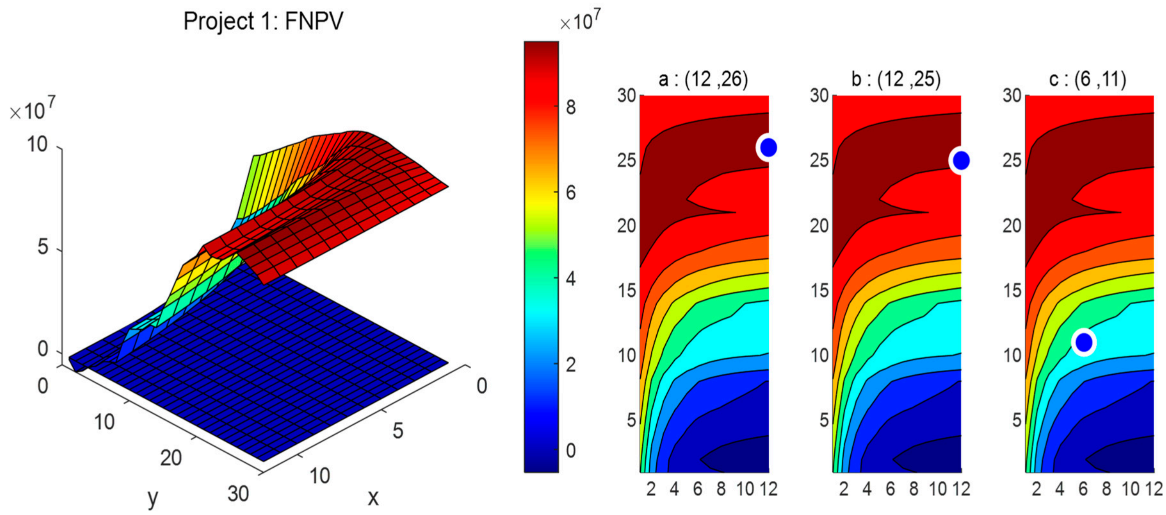

Figure 20. Decision-making for project 1.

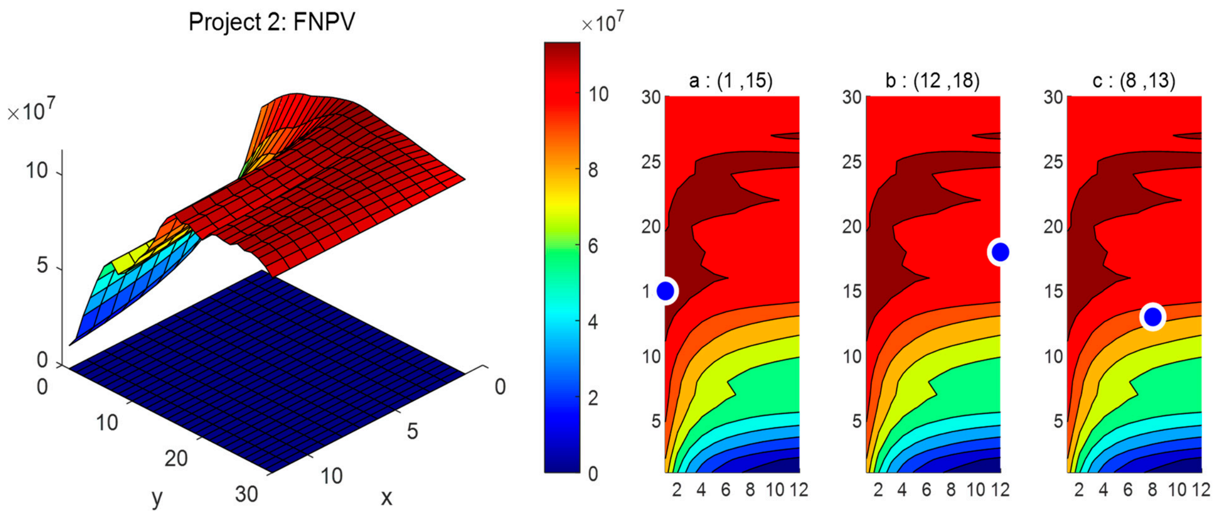

Figure 21. Decision-making for project 2.

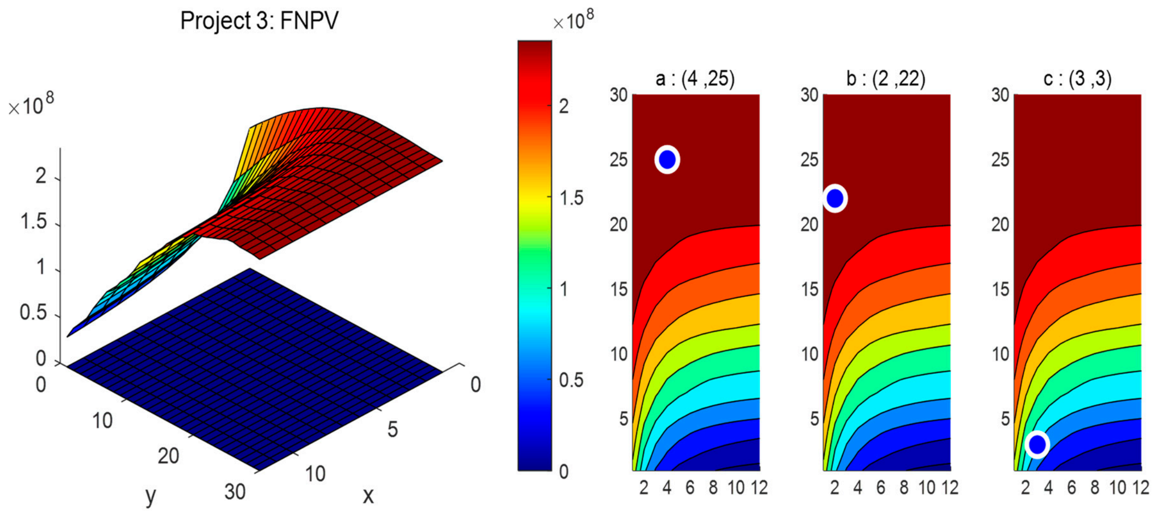

Figure 22. Decision-making for project 3.

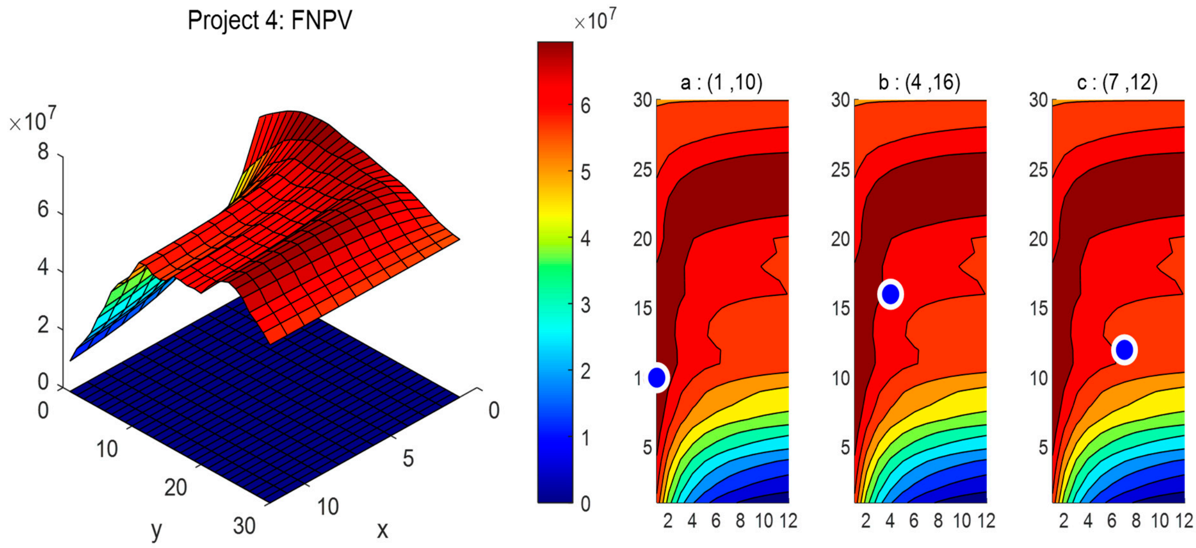

Figure 23. Decision-making for project 4.

1. Constant long-term mean value

To maintain the consistency of the analysis, the same scenario as Figure 11 is selected here. It is shown in Figure 14.

The details of the figures similar to Figure 15 in this paper are described below. These figures show the results of the enterprise's decision optimization for all projects, regarding the (x, y) combination. Here, the JET color scheme of MATLAB is used. In the figure, the hotter color represents the larger value. The left subgraph represents all combinations of (x, y) decisions of the company regarding this project in a given price scenario, and their corresponding FNPV calculations. The horizontal matrix represents the case when FNPV of this project is 0.

The right subgraph maps the results of the above calculation to the two-dimensional plane. They correspond to the achievement of (a), (b), and (c), the three decision objectives. For example, "a: (12,21)" means that the objective (a) is reachable. In this case, the combination is x = 12 and y = 21. In the subgraph, it will be marked with a blue dot. In addition, "c: None" means that the combination of decisions to achieve this objective (c) does not exist.

Note that in assuming that the enterprise's capital is its own funds, the time cost of capital does not influence the investment decision of the enterprise. Thus, when the value of the production interval is 12, it only means delaying the development as much as possible. Of course, the introduction of the time cost of capital, interest rates, and fluctuations in the exchange rate market are still extremely useful to study. This is especially true for the study of foreign investment projects, co-investment projects, and so on [58].

The analysis for the three objectives is as follows.

(a): Project 1 needs to develop as many gas wells as possible in period 1 (y = 21) and delay the development of the remaining gas wells as much as possible (x = 12). This is due to the low yield of project 1 and the high impact of the regressive effect. This strategy allows more gas wells to be exploited simultaneously in period 1. The slow development of the remaining gas wells smooths out the impact of variable costs and depreciation on current net income. This strategy will result in the highest FNPV for the project.

(b): Project 1 needs to further increase its initial capacity (y = 25), while the remaining wells need to be developed as soon as possible (x = 3). Although variable costs and depreciation have a significant impact in the medium and late stages, the best cumulative net profit of all scenarios is still achieved.

(c): Because of the lack of sustainability of project 1 in the mid and late stages, when y is small, FNPV is always negative, so it is not possible to achieve this objective.

Project 2 has a higher production and a positive FNPV is guaranteed for all scenarios. In addition, project 2 has a certain probability of having higher producing gas wells in the middle and late stages.

(a): Project 2 needs to develop appropriately fewer gas wells in period 1 (y = 16) and delay the development of the remaining wells as much as possible (x = 12). This helps the net profit of the project to remain high at mid-term.

(b): Project 2 needs to develop gas wells as much as possible in period 1 (y = 19) and accelerate development appropriately in the mid-term (x = 9). This is because there are higher producing gas wells in the middle and later stages, which helps to enhance the cumulative profit of the project.

(c): Project 2 requires further reductions in y and x. The project is still technically likely to have good production in the mid- and late-stages. Therefore, reducing the development of gas wells in period 1 and properly accelerating the development of the remaining gas wells helps the project to attain a more balanced production while maintaining FNPV > 0.

The scenario reflected in Project 3 is the most ideal, and all the options can guarantee a positive FNPV.

The analysis for the three objectives is as follows.

(a): Project 3 needs to develop as many gas wells as possible in period 1 (y = 16) and delay the development of the remaining wells as much as possible (x = 12). This helps to maintain the desired net profit in the medium term and thus achieve the maximum FNPV.

(b): Project3 needs to maintain the number of gas wells developed in period 1 (y = 7) and accelerate development in the mid-term (x = 4). This helps the project to sustain mid- stage and late-stage continuity. This will also reduce the high depreciation expense caused by developing too many wells in period 1, while maintaining the effectiveness of the investment (FNPV > 0).

(c): Project 3 needs a further reduction in y and x. This is still dependent on the better resource characteristics of the project in terms of technical impact factors. This allows the project to sustain higher production and a more balanced recovery of gas resources while maintaining investment effectiveness (FNPV > 0).

The scenario reflected in project 4 is the case where the production and decline effect are the mean value. The analysis of this project is similar to the previous three scenarios. Further, the general idea of the analysis of these projects and technology scenarios is as follows.

When the mean value of the long-term price is constant, on the one hand, the strategy of decreasing y helps to maintain the sustainability of the project in the mid-stage and late-stage. Conversely, the strategy of increasing y leads to greater production. This is because increasing the number of developed gas wells in period 1 is clearly helpful to increase production. However, this leads to high depreciation expenses, which in turn affects net profit and FNPV.

On the other hand, the strategy of increasing x also helps to further maintain the sustainability of the project. Conversely, a strategy of decreasing x can also help the project achieve greater production. However, since the production from remaining wells is usually smaller, the pacing of exploitation from subsequent wells also needs to take the expectation of gas prices into account. This makes it particularly important to consider both technical and economic influences in all project decisions.

In the following, the long-term mean value increase is discussed for comparative analysis. For the discussion of the long-term mean value decline scenario, please see Appendix A. These results are reported in Figures A3–A7.

2. Rising long-term mean value

The price scenario is shown in Figure 19.

Compared Figure 20 with Figure 15, project 1 is more investable during the gradual price increase. This is demonstrated by the positive FNPV that can be obtained for all portfolio decisions for project 1. Both objectives (a) and (b) need to be achieved by developing gas wells in period 1 as much as possible and by slowing down the development pace.

Such decisions clearly consider the impact of rising prices. This is because when prices rise, the impact of cash outflows from depreciation will be significantly offset by net cash inflows from sales revenues. This effect is more pronounced in the mid-stage and late-stage of the project.

Compared Figure 21 with Figure 16, project 2 will have better FNPV, and because this project still has a higher probability of producing high-production wells in the mid and late stages, it needs to be developed at as fast a pace as possible to achieve a higher FNPV for objective (a). It is opposite for objective (b). This is because, under this strategy, the project will remain more profitable in the medium and late stages.

Compared to project 2, project 3 has a higher production. Therefore, compared Figure 22 with Figure 17, project 3 needs to further increase y and decrease x when the price rises. This will increase the FNPV and achieve objective (a). Further, consider the price scenario in Figure 19 where the price rises significantly in the early stages and remains high in the middle and late stages. Therefore, the project needs to raise y and lower x to obtain higher cumulative net cash flow during the price increase phase and achieve objective (b).

In Figure 23, the analysis of the mean case reflected in project 4 is similar to that of Figure 18. Overall, increasing y contributes to higher net cash inflows when prices rise. However, this is more clearly reflected in the change in the decision on x. This change is mainly reflected in the fact that when prices rise, x will all decrease and the pace of exploitation will be faster. For projects 2 and 3, which have better technical assessments, such a strategy also allows them to achieve higher economic returns in the rising price phase.

The above analysis suggests that these project scenarios will all obtain better returns when long-term prices gradually increase. A combined strategy of increasing the development of wells at period 1 and accelerating the development of the remaining wells would further enhance the returns of these projects.

It is worth noting that objective (c) seems to be more focused on technical factors. However, this is mainly the case for projects with better technical evaluation results, such as projects 2, 3, and 4, but for project 1, the combination strategy to achieve it is, indeed, non-existent. Therefore, these results reflect that both technical and economic factors need to be fully and integrally considered when making decisions on investment options for conventional gas projects.

5. Conclusions

This paper constructs an analytical framework for the economic evaluation of conventional natural gas projects in the capacity building and planning phases. Through the modeling and numerical simulation approaches, the following general conclusions are suggested.

(1) Technical and economic uncertainties are objectively present in the investment activities of conventional natural gas projects, and the impact of both needs to be systematically considered.

(2) The evaluation of an enterprise's investment plan under different decision objectives will be structurally influenced by technical and economic factors. This is particularly important for large state-owned natural gas enterprises in China. For the plan that prioritizes technical factors with resource recovery, there is a need to increase capacity technology and accelerate the overall development schedule. This strategy could obtain more gas resources in a short period of time. However, this strategy will make the project more vulnerable to price declines in international markets and to shocks from substitutes. For a plan that prioritizes financial returns, a more precise assessment of long-term price trends for natural gas is required.

(3) It is necessary for enterprises to carry out scientific technical and economic assessments and to develop investment plans. These plans are differentiated and can be dynamically optimized. In conjunction with the research in this paper, projects with better technical assessments may have better economic returns when prices are expected to rise. Enterprises need to invest more in such projects and accelerate their development. Conversely, when the expected price decreases, projects with poorer technology

assessment need to reduce investment and slow down development. In these differentiated investment scenarios, the technical and economic assessment is dynamic and can be dynamically optimized.

Therefore, the novel points of this paper are as follows.

(1) This paper integrates the technical and economic research perspectives of conventional natural gas projects. By introducing multiple uncertainties, this paper integrates this technical and economic research paradigm into a unified framework. Its strength lies in two points. First, it allows for the economic evaluation of investment plans from the perspective of analyzing technical influences. Second, it can also adjust the technical solutions from the perspective of analyzing the economic impact factors and objectives.

(2) Using numerical simulations of approaches, the process of investment decision optimization by companies based on technology assessment and price forecasting is visualized in detail. Within this framework, this paper focuses on the optimization behavior of investment decisions of natural gas upstream companies. Currently, in China, the main investors in these conventional natural gas projects are state-owned enterprises. When making investment decisions, these enterprises need to consider not only the technical and economic implications, but also their business status and social responsibility. Therefore, there are multiple objectives. The framework in this paper could be used for a more detailed analysis and provides decision aids.

(3) The research framework and its algorithms proposed in this paper has good scalability. Based on the availability of data, the framework proposed in this paper can be further calibrated with more advanced statistical analysis and big data analysis techniques to further calibrate the relevant parameters, including Technical factors such as production and declining rate, dynamic demand, and international energy price fluctuations. Moreover, richer functions can be constructed to portray the impact of the game among various entities in the natural gas industry chain. This can also portray the mechanism of the macroeconomic, policy and regulation, and international investment environment on energy project competition and cooperation.

In addition, there are some shortcomings and expandable directions in the research of this paper.

(1) The analysis of technical and economic uncertainty needs to be more fully integrated with the external environment. This enables the construction of an analytical framework that encompasses a richer and more comprehensive range of uncertainties. This paper simplifies these factors, but still retains a scalable analytical interface. The analysis of price and volatility factors traded in natural gas markets is necessary. At the same time, volatility spillovers to the natural gas market are likely to occur in the bulk energy commodity and its derivatives markets. In addition, factors such as the international and domestic political environments, interest rates, exchange rates, and government-directed project benchmark rates of return will have a significant impact on the investment program [58,59].

(2) With the availability of data, it is important to conduct extensive enterprise data analysis. In such projects, variable costs are usually divided into dozens of items that have different mechanisms to influence the variable costs of the project. The amount of investment has a significant impact on depreciation. In turn, the investment amount is influenced by many uncertainties in the exploration and resource evaluation phase. In the extended interface of this framework, these factors can be introduced gradually. In addition, cost management, financial risk management, and investment and financing management of enterprises will be able to be studied more scientifically.

Based on the above analysis, the research framework of this paper can be further aligned with the technical research perspective of natural gas or expanded to macro or meso economic and management research. These further studies could provide more suggestions for energy research.

Author Contributions: Conceptualization, C.Y. and M.T.; methodology, C.Y. and M.T.; writing—original draft preparation, C.Y. and Z.Y.; writing—review and editing, J.Z.; visualization, C.Y. and M.T.; supervision, M.T.; project administration, C.Y. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The codes presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

1. Static analysis for evaluation of investment plan

Section 4.2.2 discusses the production, after-tax income, total cost, and net profit for project 1 and project 2, under the portfolio strategy (6, 4). The first part of Appendix A reports project 3 and project 4 under this portfolio strategy. It is shown in Figures A1 and A2.

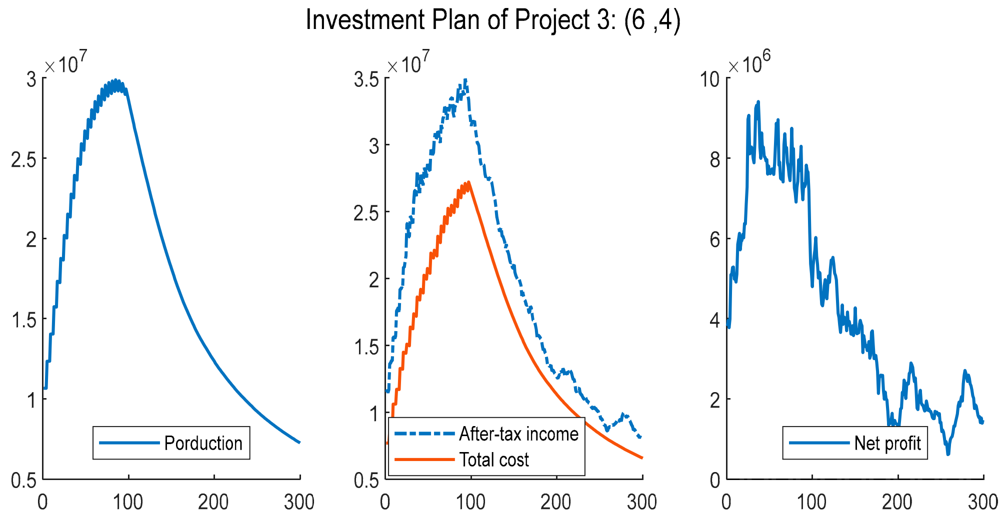

Figure A1. Production, income, cost, and net profit of project 3.

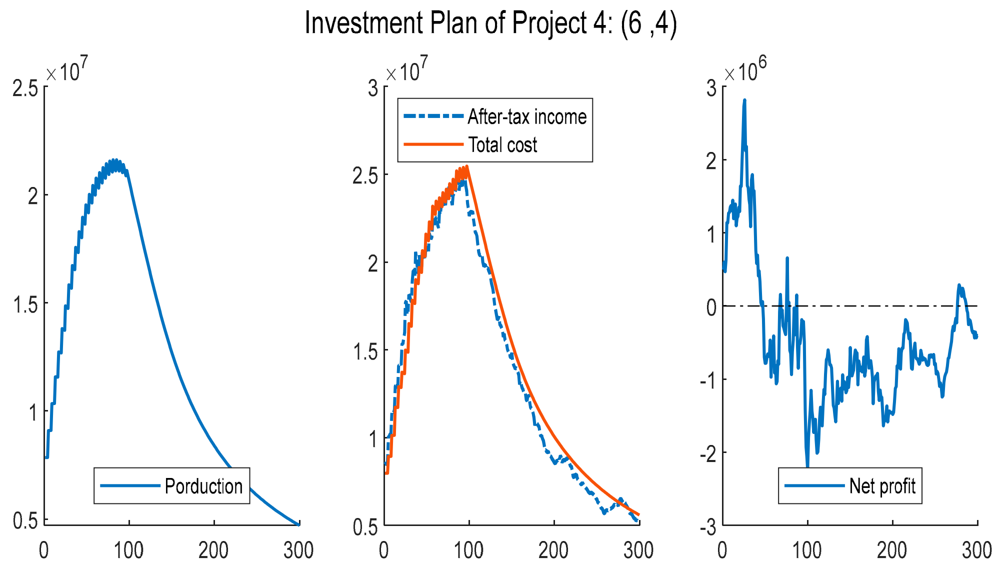

Figure A2. Production, income, cost and, net profit of project 4.

Project 3 reflects the scenario where production is more ideal, and project 4 reflects the scenario where production and the effect of decline effects are averaged. In these scenarios, production, after-tax income, total cost, and net profit are better than in projects 1 and 2. In the process of declining production (around period 100), the law of declining is more directly reflected. Considering that the price increases with significant fluctuations around the 200th period, these project scenarios still seem to have better economics in the late-stage.

2. Decision optimization at long-term mean decline

In Section 4.2.3, investment decisions and optimization with the long-term mean value is constant, and increases are examined. Part 2 of Appendix A reports the results of the long-term mean value decrease.

When these possible long-term price decline scenarios occur, the investment economics of each of these project scenarios will be significantly impacted. While adjusting the results of the technology assessment to the ideal state (as in project 3) appears to achieve the three decision objectives, the average value of the technology assessment (as in project 4) reflects that these projects still require prudent investment

In particular, note that in this paper the benchmark rate of return is used to calculate the FNPV of the project. It obviously has a direct impact on the results of the FNPV calculation, as well as the objectives of the decision. In China, benchmark yields are usually set by the government administration as a guideline value. However, these values are different for conventional and various types of unconventional gas projects. There may also be room for fluctuations in underlying yields. These are still under discussion. Therefore, the framework proposed in this paper may be interesting in terms of an extension of this research perspective.

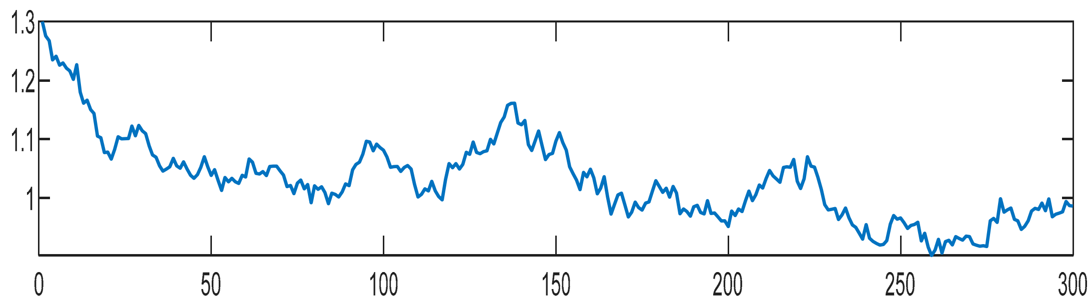

Figure A3. Selected mean value decrease scenario of gas prices.

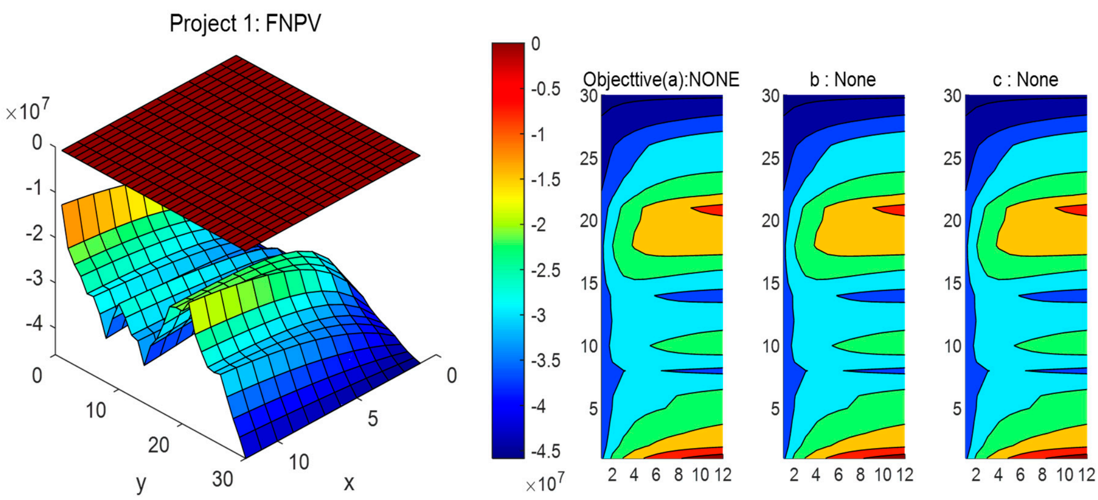

Figure A4. Decision-making for project 1.

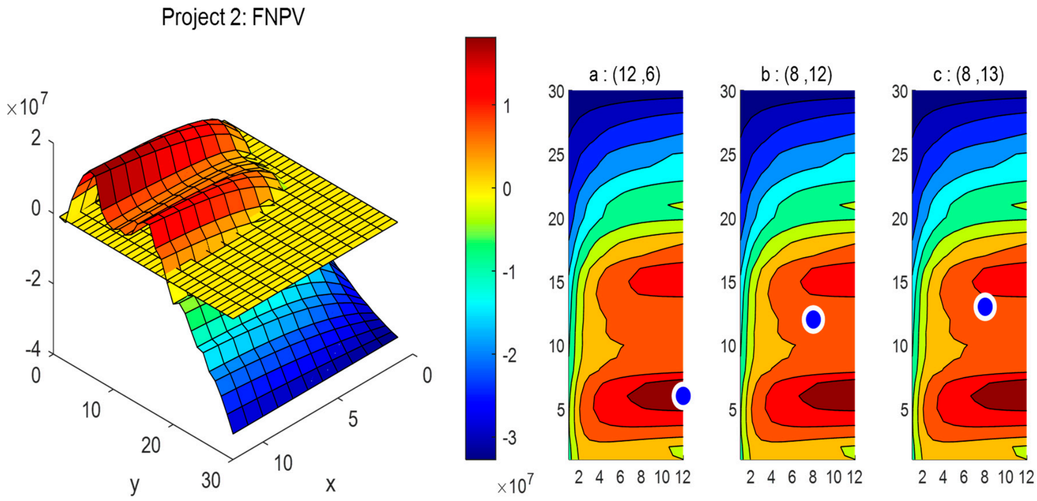

Figure A5. Decision-making for project 2.

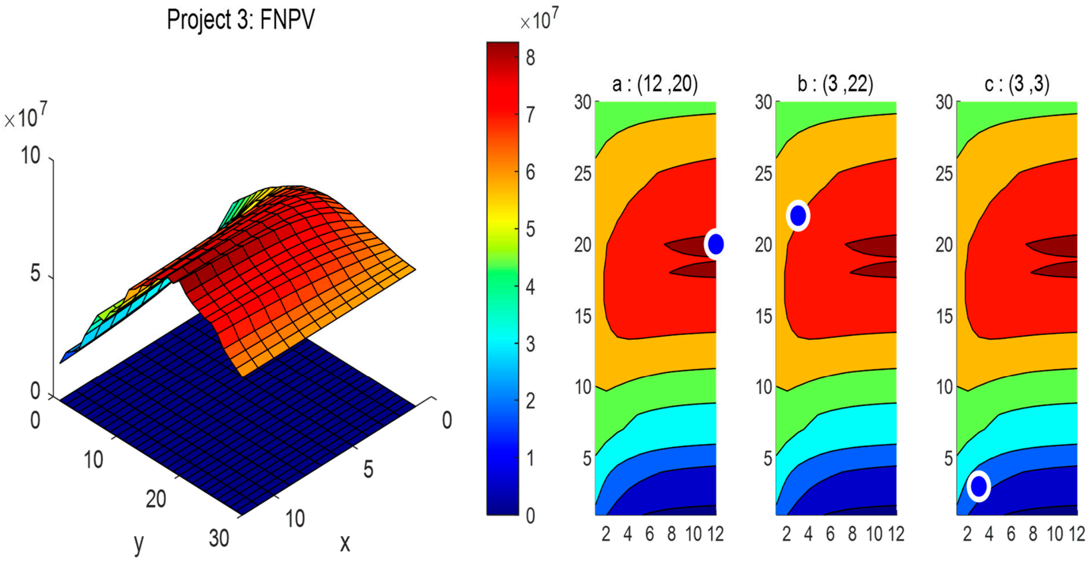

Figure A6. Decision-making for project 3.

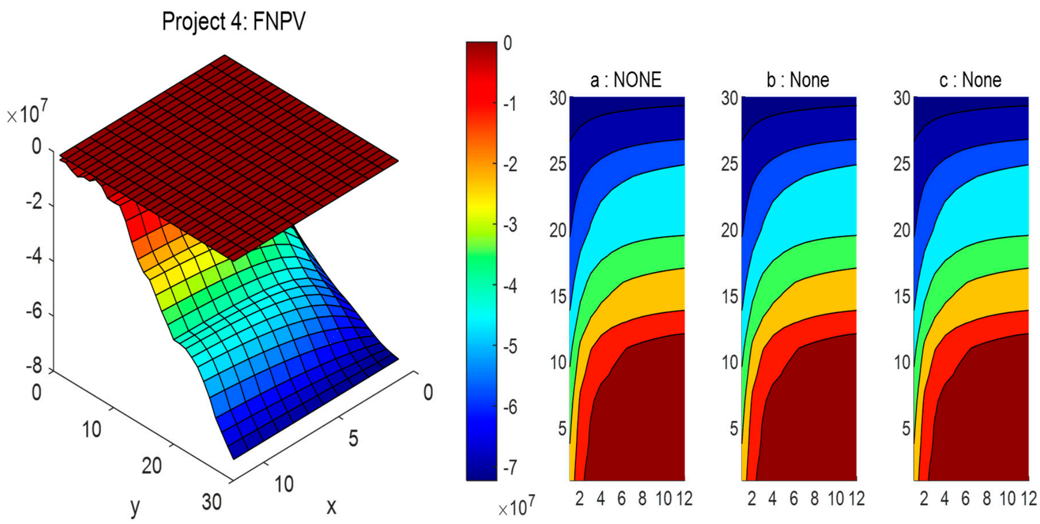

Figure A7. Decision-making for project 4.

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