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Evaluation of the Coordination Degree of Coal and Gas Co-Mining System Based on System Dynamics

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Abstract: Coal and gas co-mining is one of the green mining technologies in coal mines. Coal and gas co-mining can reduce environmental pollution and supply-side carbon emissions from the coal industry. It has an important role to play in achieving the goal of carbon peaking and carbon neutrality. The perfect state of safety production and economic efficiency is a "win-win" situation. Therefore, it is of great theoretical and practical importance to evaluate the safety and economic coordination of coal and gas co-mining systems. This study used a system dynamics approach to analyze and evaluate the coordination of coal and gas co-mining systems in a dynamic simulation. A case study was conducted using the Zhuxianzhuang coal mine as an example. The results showed that the coordination degree of the coal and gas co-mining system exhibited dynamic changes. The average value of the system coordination degree is 0.790, which is a good coordination degree. This demonstrates that the system dynamics method is feasible for evaluating the coordination degree of the coal and gas co-mining system. The system dynamics evaluation model can effectively simulate the dynamic changes of different variable factors in the co-mining system. Therefore, these research results can provide corresponding optimization recommendations for practical production needs.

Keywords: system dynamic model; simulation analysis; co-mining of coal and gas; coordination degree evaluation

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1. Introduction

To address global warming and accelerate global greenhouse gas emission reduction, China proposed the goal of "carbon capping and carbon neutrality" at the 75th session of the United Nations General Assembly in September 2020 [1]. In the context of the "carbon peaking and carbon neutrality" goal, coal extraction is both an important source of energy supply and a major source of greenhouse gas emissions [2–4]. In addition to carbon dioxide, greenhouse gases include methane, nitrous oxide, and sulfur hexafluoride, which are collectively referred to as non-carbon dioxide greenhouse gases by the international community. Methane (CH_4) is the second most important greenhouse gas after carbon dioxide. The greenhouse effect of a methane molecule is more than 20 times that of a carbon dioxide molecule. The *6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* has proposed global medium- and long-term coal and gas emission reduction goals around achieving different temperature control goals [5]. This increases the pressure on the global mining industry to decarbonize coal mining and consumption for minimizing coal mine methane emissions, which is an actual scientific and technical problem [6].

The main source of energy in China is coal, which is extremely rich in energy reserves [7]. However, the discovered coal resources account for a relatively small proportion of the coal reserves. With China's rapid economic development, coal demand is gradually increasing. According to statistics, coal consumption in 2021 accounts for 56.0% of total energy consumption [8]. It leads to a gradual increase in the depth of coal mining in China as well. AS the depth of mining increases, coal bed methane pressure and gas gushing are increasing, and the danger is significantly increasing. Gas, as an associated product of coal, is mainly composed of methane (CH_4). While it is a source of disaster and air pollution in coal mines, it is also a valuable, clean, and efficient non-renewable energy source from the carbon footprint perspective [9]. The extraction of gas can improve the safety of mining production and protect the environment. It can also improve the coordination of resource, economic, safety, and environmental factors, ensuring that the coal industry can maximize its benefits and also the sustainable development of society within the corresponding constraints.

Coal and gas co-mining is a method of mining both coal and gas as resources. Compared to traditional coal mining, coal and gas co-mining has the characteristics of reducing greenhouse gas emissions in the atmosphere, improving economic benefits, reducing gas hazards, and lowering ventilation costs. The premise of the coal production system is safe production, and it aims to ensure maximum economic benefits in a safe state. Therefore, in the background of the "double carbon" goal, a coordinated degree evaluation of the safety and economy of coal and gas co-mining can be a good contribution to mine production.

Dzhioeva, A.K. et al. [10] describe the non-linear variation of methane concentrations in subsurface boreholes and the specific characteristics of their implementation. Brigida, V.S. et al. [11] studied the characteristics of local minimum methane concentrations in drainage holes. Bing Qin et al. [12] pointed out that the stress redistribution caused by coal and gas co-mining mining affects the permeability and thus the gas co-mining. At present, many scholars' research on coal and gas co-mining is mostly focused on the research co-mining theory, the influence of pressure relief for outgassing dynamics, technological processes, and related questions [13–17], while the research on the evaluation of coal and gas co-mining remains insufficiently studied. Zhiheng Cheng et al. [18] constructed a co-mining technology system and dynamic evaluation model for determining the effect of extraction-mining-extraction on coal seam clusters near the mine area. Bing Liang et al. [19] established a fuzzy comprehensive evaluation model with three parts: economic pre-evaluation, safety evaluation, and co-mining effect. On this basis, it quantified the degree of coordination between coal mining and gas extraction systems using the coordination degree function. The evaluation of coal and gas co-mining has mainly focused on the evaluation of co-mining effectiveness. The dynamic assessment of the coordination degree of the co-mining system is a less studied area.

In this paper, the possibility of application is being considered the System Dynamics method to co-production system coordination assessments. The co-mining system is divided into economic benefits and safety levels according to production and operational objectives. Then the system dynamics method is used to establish the corresponding coordination evaluation model of the co-mining system. Finally, it is simulated and evaluated, and rationalization recommendations are given.

2. Materials and Methods

2.1. Dynamic Evaluation Methods

System Dynamics (SD) is a method for studying the structure of systems created by Forrester [20]. It is a dynamic evaluation method. System dynamics uses the theory and method of information feedback to study complex systems. It is argued that its behavior patterns and properties depend mainly on its internal dynamic structure and feedback mechanisms. System dynamics can solve highly nonlinear, high-order, multivariate, multi-feedback, and complex system problems. It can grasp the trend of development of things at the macroscopic level as well as analyze the interactions of microscopic factors within the system. Currently, system dynamics methods have been successfully applied to risk assessment [21], efficiency evaluation [22], resource contribution evaluation [23], policy evaluation [24], and economic benefits evaluation [25].

This paper adopts a system dynamics-based method for evaluating the coordination of coal and gas co-mining systems. The coal and gas co-mining system is dynamic, and its structure as well as the economic benefits and safety level in the production process can be seen as a complex system. The dynamic evaluation of the coordination degree of coal and gas co-mining systems first requires consideration of the system as a whole. Secondly, the influence constraints between the indicators of the system and between the indicators and other relevant factor variables are summarized, taking into the characteristics of coal and gas co-mining into account. Finally, a system dynamics model is established for the evaluation of the coordination degree of the co-mining system. The level of coordination of the coal and gas co-mining system and the trend behavior of the results of other variables over time is obtained through simulation analysis. Based on this, key factors are selected to study the degree of influence of different influencing factors on the coordinated development of the co-mining system, and then optimization suggestions for mine production are provided.

2.2. Construction of System Dynamics Indexes

The system dynamics cause-effect diagram is a reflection of the cause-effect relationship between various factors of the system, which is the basis of the final simulation flow diagram of the system. The coal and gas co-mining system is a multi-level and multi-factor complex system. The maximization of efficiency and safe production are important goals pursued by the enterprise. The system coordination evaluation in this paper will focus on these two goals and divide them into the economic benefits subsystem and the safety level subsystem. Through a literature research and data collation, factors affecting the coordination of the coal and gas co-mining system were distilled [19,26–29]. We then distributed questionnaires on the influencing factors to people working in coal-related industries to filter the indicators and obtain the final subsystem factors and influencing factors. Finally, combining the characteristics of the coal and gas co-mining system, the relationship between the influencing factors in the system is analyzed, and the cause-and-effect diagrams of its economic efficiency sub-system, safety level sub-system, and coal and gas co-mining system are constructed.

2.2.1. Economic Benefits Subsystem

The economic benefits of the coal and gas co-mining systems are influenced by the level of geology, technology, economy, and environment. The feedback relationship of the economic benefit subsystem is shown in Figure 1. In the figure, "+" indicates a positive correlation, and "−" indicates a negative correlation. The main feedback relationships include:

(1) Depth of coal seam buried → (−) Geological level of coal seam → (+) Geological level → (+) Economic benefits
(2) Coal seam thickness → (+) Geological level of coal seam → (+) Geological level → (+) Economic benefits
(3) Top and bottom slab lithology → (+) Basic geological level → (+) Geological level → (+) Economic benefits
(4) Hydrogeological situation → (−) Basic geological level → (+) Geological level → (+) Economic benefits
(5) Complexity of geological structure → (−) Basic geological level → (+) Geological level → (+) Economic benefits
(6) The degree of difficulty of gas extraction → (−) Gas geological level → (+) Geological level → (+) Economic benefits
(7) Gas content → (+) Gas geological level → (+) Geological level → (+) Economic benefits
(8) Gas pressure → (+) Gas geological level → (+) Geological level → (+) Economic benefits
(9) Coal mining rate → (+) Technical level → (+) Economic benefits
(10) Gas mining rate → (+) Technical level → (+) Economic benefits
(11) Coal price → (+) Economic level → (+) Economic benefits
(12) Production cost → (−) Economic level → (+) Economic benefits
(13) Total investment → (−) Economic level → (−) Economic benefits
(14) Land reclamation rate → (+) Environmental level → (+) Economic benefits
(15) Wastewater utilization rate → (+) Environmental level → (+) Economic benefits
(16) Gas emission utilization rate → (+) Environmental level → (+) Economic benefits

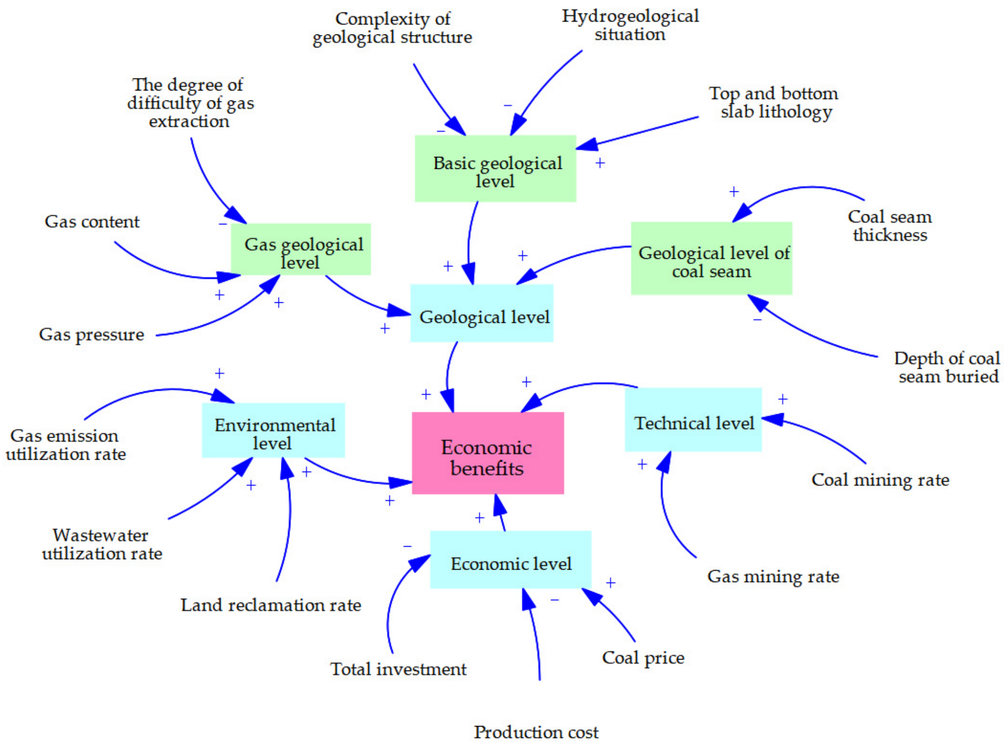


Figure 1. Cause and effect analysis of economic benefits.

2.2.2. Safety Level Subsystem

The safety level of the coal and gas co-mining systems is influenced by the level of gas geology, the level of basic geology, the level of inputs, and the level of production. The feedback relationship of the safety level subsystem is shown in Figure 2. In the figure, "+" indicates a positive correlation, and "−" indicates a negative correlation. The main feedback relationships include:

(1) Hydrogeological situation → (−) Basic geological level → (+) Safety level
(2) Complexity of geological structure → (−) Basic geological level → (+) Safety level
(3) Top and bottom slab lithology → (+) Basic geological level → (+) Safety level
(4) Gas pressure → (+) Gas geological level → (−) Safety level
(5) Gas content → (+) Gas geological level → (−) Safety level
(6) The degree of difficulty of gas extraction → (−) Gas geological level → (−) Safety level
(7) Electrical and mechanical equipment integrity rate → (+) Production level → (+) Safety level
(8) Education level of personnel → (+) Production level → (+) Safety level
(9) Number of extraction roadway layout → (+) Input level → (+) Safety level
(10) Number of drill holes arranged in the mining site → (+) Input level → (+) Safety level
(11) Production cost → (+) Input level → (+) Safety level
(12) Relative gas emergence volume → (+) Gas level → (−) Safety level
(13) Return airflow gas concentration → (+) Gas level → (−) Safety level

The cause-and-effect diagram of the coal and gas co-mining system is built based on the analysis of the relationship between the variables of the economic benefits and safety level subsystems. The cause-effect relationship of the coal and gas co-mining system is shown in Figure 3.

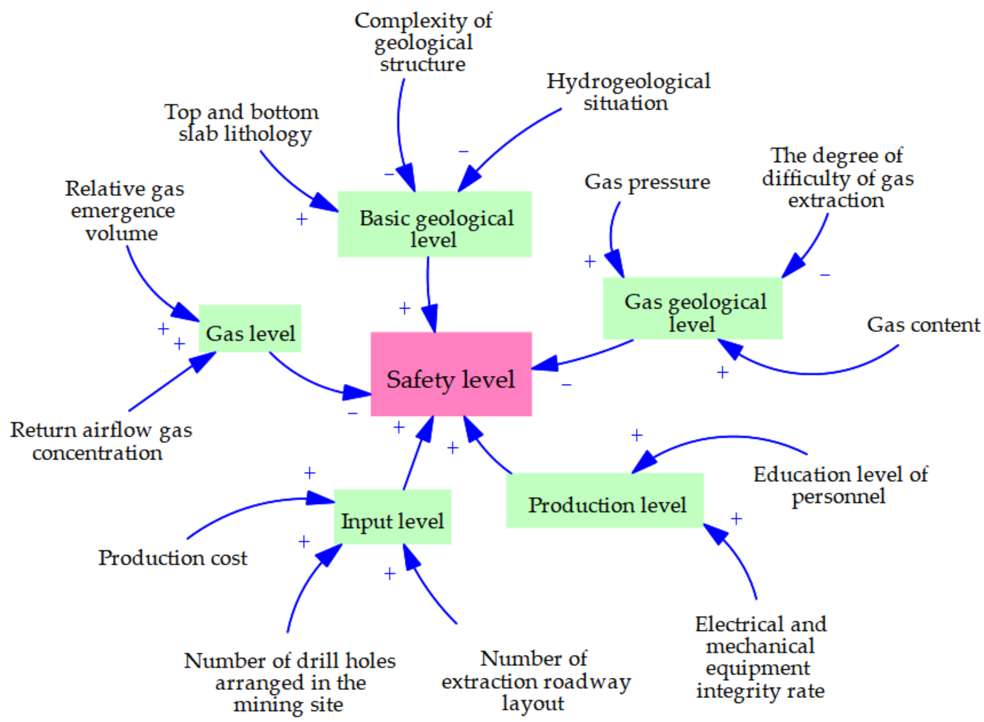


Figure 2. Cause and effect analysis of safety level.

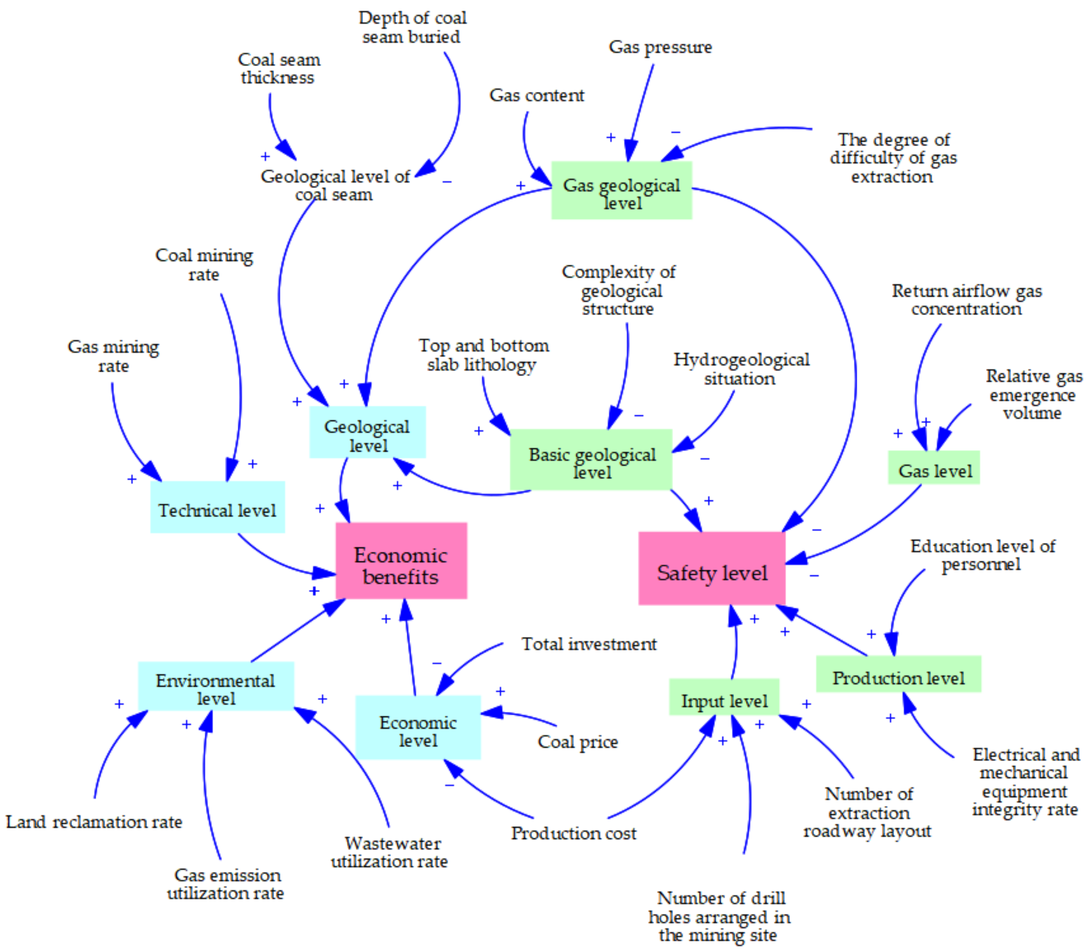


Figure 3. Cause and effect analysis of coal and gas co-mining system.

2.3. System Dynamics Model

By analyzing the relationship between the variables of the economic benefits and safety level subsystems, and combining the variable relationships between the subsystems, a coal and gas co-mining system dynamics model was constructed using Vensim PLE 9.2.4 software, as shown in Figure 4.

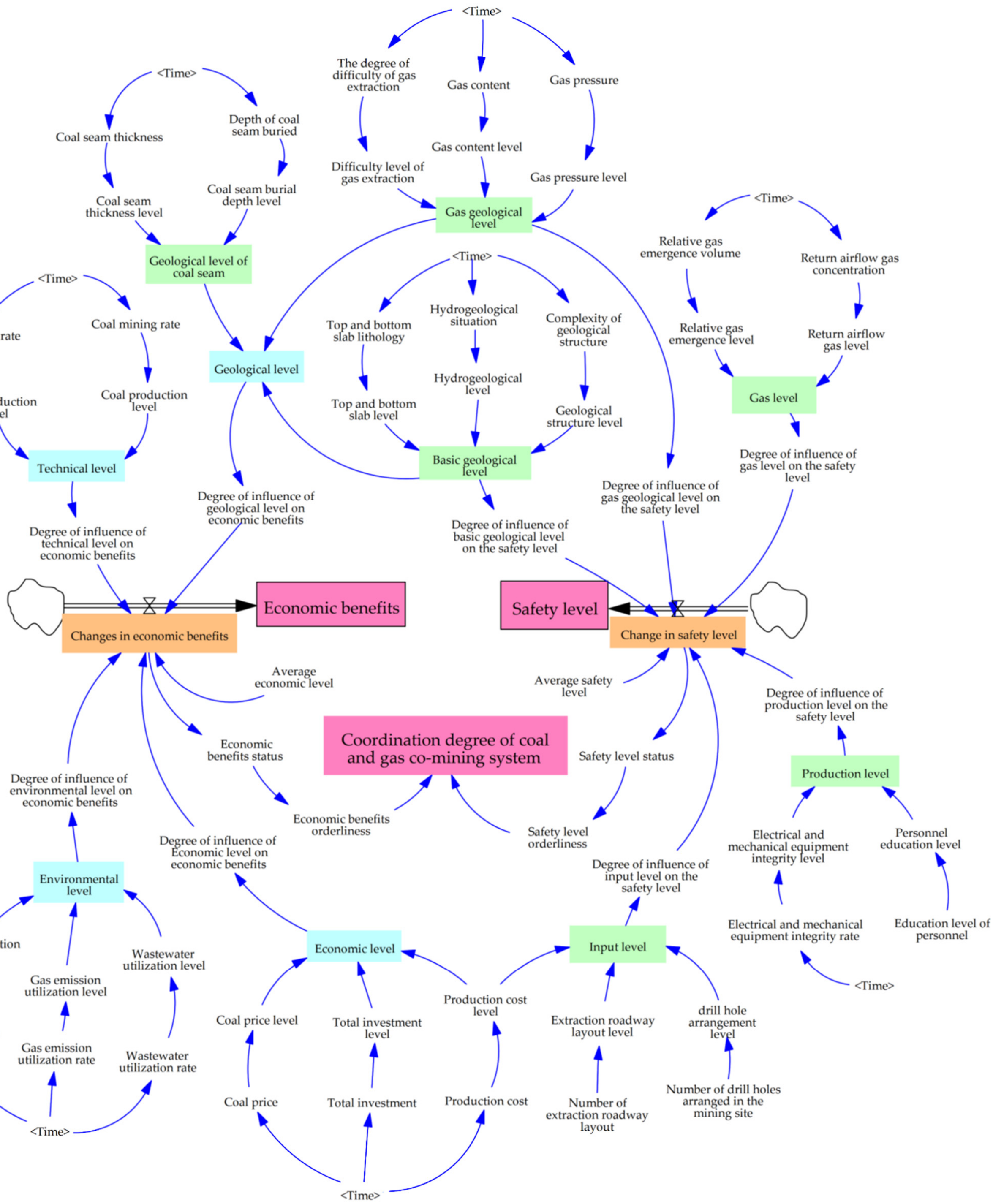


Figure 4. System dynamics model of the coordination degree of the coal and gas co-mining system.

3. Case Study

The Zhuxianzhuang coal mine is mainly for fully mechanized top coal caving, and the degree of mechanization is 100%.

It adopts the method of coal mining with strike longwall and all trap roofs.

It uses an advanced mining sequence in the mining area and a backward mining sequence in the section. For gas protruding working faces, high-level boreholes and upper-corner buried pipes are mainly used to extract gas from the mining area during the recovery period.

Taking the II851 working face as an example, its coal seam original gas pressure is 1.55 MPa and its original coal seam gas content is 9.71 m^3/t. The working face was located in the protrusion risk area. It adopted the measures of protection layer mining combined with a hole drilled along seam-enhanced gas drainage and the coal mining method of strike longwall full seam cutting.

3.1. Parameters

3.1.1. Determination of Parameters

In this study, we used the coal and gas co-mining system at the Zhuxianzhuang coal mine as a case study. The simulation was carried out using Vensim PLE 9.2.4 software to establish the coordination degree dynamic model of the coal and gas co-mining system. The simulation time was set at 12 months to accommodate the effects of different climates on coal mining and gas extraction. The data for the model comes from the 2020 statistics for the Zhuxianzhuang Mine. The model data includes some constants and variables, and the model data values are taken based on monthly average data. The variables are coal seam thickness, coal seam burial depth, coal production rate, gas production rate, coal price, etc. The principles of influence level and influence degree of each variable in the model are as follows.

(1) Influence level assignment

The degree of influence of each variable in the system dynamics model varies with its value. By using the table function of the Vensim PLE 9.2.4 simulation software, the change in the value of the influence factor corresponds to its level of influence. Finally, the level of influence is then quantified in a range of scores from 40 to 100.

(2) Influence degree assignment

The degree of influence is the degree of influence of the influence factor on the corresponding influence object in the system. The greater the degree of influence means that the greater the promotion of the influence object. Conversely, the greater the weakening effect. The influence degree is taken as a value between 0.5 and 1.5.

3.1.2. Coordination Degree Function

$U_{i(sj)}$ indicates the degree of ordering of the variable x_j on the system. ω_j indicates indicator weighting. In this paper, the geometric average method is integrated with the linear weighted sum method. The integrated function is called the coordination degree function.

(1) Geometric average method

$$D = \sqrt[n]{U_{i(s1)}U_{i(s2)}\dots U_{i(sj)}} = \sqrt[n]{\prod_{j=1}^{n} U_{i(sj)}} \tag{1}$$

(2) Linear weighting method

$$F = \sum_{j=1}^{n} \omega_j U_{i(sj)} \tag{2}$$

Finally, the coordination degree function is constructed as follows.

$$C = \sqrt{D \times F} \tag{3}$$

3.1.3. Equations

The equation in the model flow diagram is:

(1) Coordination degree of coal and gas co-mining system = ((safety level orderliness × economic benefits orderliness)ˆ(1/2) × (economic benefits orderliness × W1 + safety level orderliness × W2))ˆ(1/2)
(2) Changes in economic benefits = average economic level × (degree of influence of geological level on economic benefits × W3 + degree of influence of technical level on economic benefits × W4 + degree of influence of environmental level on economic benefits × W5 + degree of influence of economic level on economic benefits × W6)
(3) Geological level = basic geological level × W7 + geological level of coal seam × W8 + gas geological level × W9
(4) Geological level of coal seam = coal seam thickness level × W10 + coal seam burial depth level × W11
(5) Gas geological level = gas pressure level × W12+gas content level × W13 + difficulty level of gas extraction × W14
(6) Basic geological level = geological structure level × W15 + hydrological level × W16 + top and bottom slab level × W17
(7) Technical level = coal production level × W18 + gas production level × W19
(8) Environmental level = land reclamation level × W20 + wastewater utilization level × W21 + gas emission utilization level × W22
(9) Economic level = total investment level × W23 + coal price level × W24 + production cost level × W25
(10) Change in safety level = average safety level × (degree of influence of basic geological level on safety level × W26 + degree of influence of input level on safety level × W27 + degree of influence of gas geological level on safety level × W28 + degree of influence of gas level on safety level × W29 + degree of influence of production level on safety level × W30)
(11) Gas level = return airflow gas level × W31 + relative gas emergence level × W32
(12) Production level = personnel education level × W33 + electrical and mechanical equipment integrity level × W34
(13) Input level = extraction roadway layout level × W35 + production cost level × W36 + drill hole arrangement level × W37

3.1.4. Determination of Weights

In this paper, we chose the hierarchical analysis method to determine the weights, and they are shown in Table 1.

Table 1. Simulation indicator weights.

Indicators	Indicates a Function	Weights
Economic benefits orderliness	W_1	0.35
Safety level orderliness	W_2	0.65
Degree of influence of geological level on economic benefits	W_3	0.2347
Degree of influence of technical level on economic benefits	W_4	0.4148
Degree of influence of environmental level on economic benefits	W_5	0.0662
Degree of influence of Economic level on economic benefits	W_6	0.2802
Basic geological level	W_7	0.1893
Geological level of coal seam	W_8	0.4163
Gas geological level	W_9	0.3944
Coal seam thickness level	W_{10}	0.3056
Coal seam burial level	W_{11}	0.6944
Gas pressure level	W_{12}	0.3366
Gas content level	W_{13}	0.3978

Table 1. *Cont.*

Indicators	Indicates a Function	Weights
The difficulty level of gas extraction	W_{14}	0.2656
Geological structure level	W_{15}	0.1219
Hydrogeological level	W_{16}	0.1124
Top and bottom slab level	W_{17}	0.7657
Coal production level	W_{18}	0.491
Gas production level	W_{19}	0.509
Land reclamation level	W_{20}	0.5193
Wastewater utilization level	W_{21}	0.1358
The gas emission utilization level	W_{22}	0.3449
Total investment level	W_{23}	0.277
Coal price level	W_{24}	0.2814
Production cost level	W_{25}	0.4416
Degree of influence of basic geological level on safety level	W_{26}	0.1086
Degree of influence of input level on safety level	W_{27}	0.2395
Degree of influence of gas geological level on safety level	W_{28}	0.227
Degree of influence of gas level on safety level	W_{29}	0.2718
Degree of influence of production level on safety level	W_{30}	0.1531
Return airflow gas level	W_{31}	0.4288
Relative gas emergence level	W_{32}	0.5712
Personnel education level	W_{33}	0.0839
Electrical and mechanical equipment integrity level	W_{34}	0.9161

3.2. Dynamic Simulation and Analysis of Results

3.2.1. Model Validation

According to the established system dynamics model, initial settings were made for the data of the Zhuxianzhuang coal mine. The simulation of the degree of coordination of the co-mining system in the Zhuxianzhuang coal mine was carried out. To make the final model simulation results more objective and accurate, economic benefits are used in the model simulation to test the validity of the model. In the simulation result after the operation, the economic benefits were 1.0399 billion yuan. Compared with its actual economic benefits of 1.008 billion yuan, the difference was 0.0319 billion yuan. The deviation rate was +3.165%. The error was within $\pm 10\%$, and the relative error was small. The simulation results of the model are relatively consistent with the actual situation. The model test results were good. The model can be used to evaluate the coordination degree of the coal and gas co-mining system.

3.2.2. Results

The specific simulation results are shown below.

The relationship between the economic benefits and safety level and the coordination degree of the coal and gas co-mining system is shown in Figure 5.

From Figure 5, it can be seen that the coordination degree of the coal and gas co-mining system shows dynamic changes. Both economic benefits and safety levels have an impact on the coordination degree of coal and gas co-mining systems, and the overall change trend is the same. Analyzing the simulation data, we can get that the average value of the coordination degree of the coal and gas co-mining system is 0.790, the evaluation of economic benefit is good, and the safety level is evaluated as average.

An analysis of the dynamic change simulation data produces the following results. The coordination degree of February and August is relatively good, and its economic benefits and safety level evaluation is relatively good, which is in the peak position in 12 months. The coordination degree of May and December is relatively poor. May has a lower evaluation of economic benefits and is in a trough position during the 12 months. December has a low level of safety and is at the lowest level in the 12 months. Therefore, economic benefits and safety levels can be improved by taking corresponding measures to ensure the production of coordinated coal and gas co-mining.

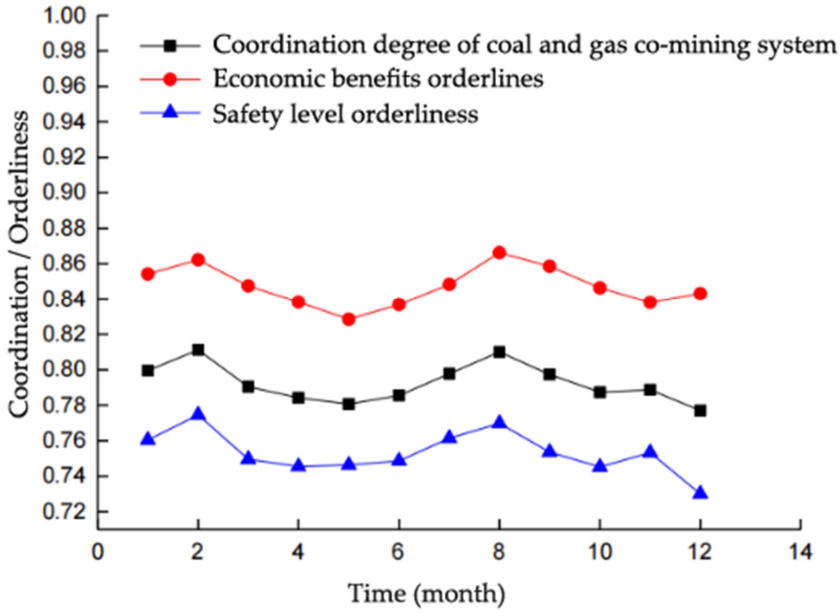
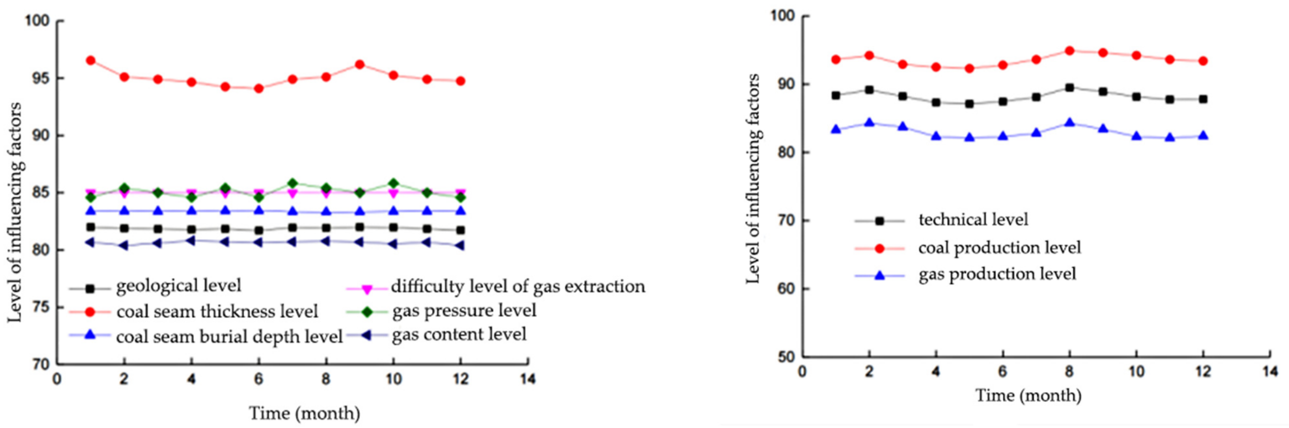


Figure 5. Relationship between economic benefits and safety level and coordination of the co-mining system.

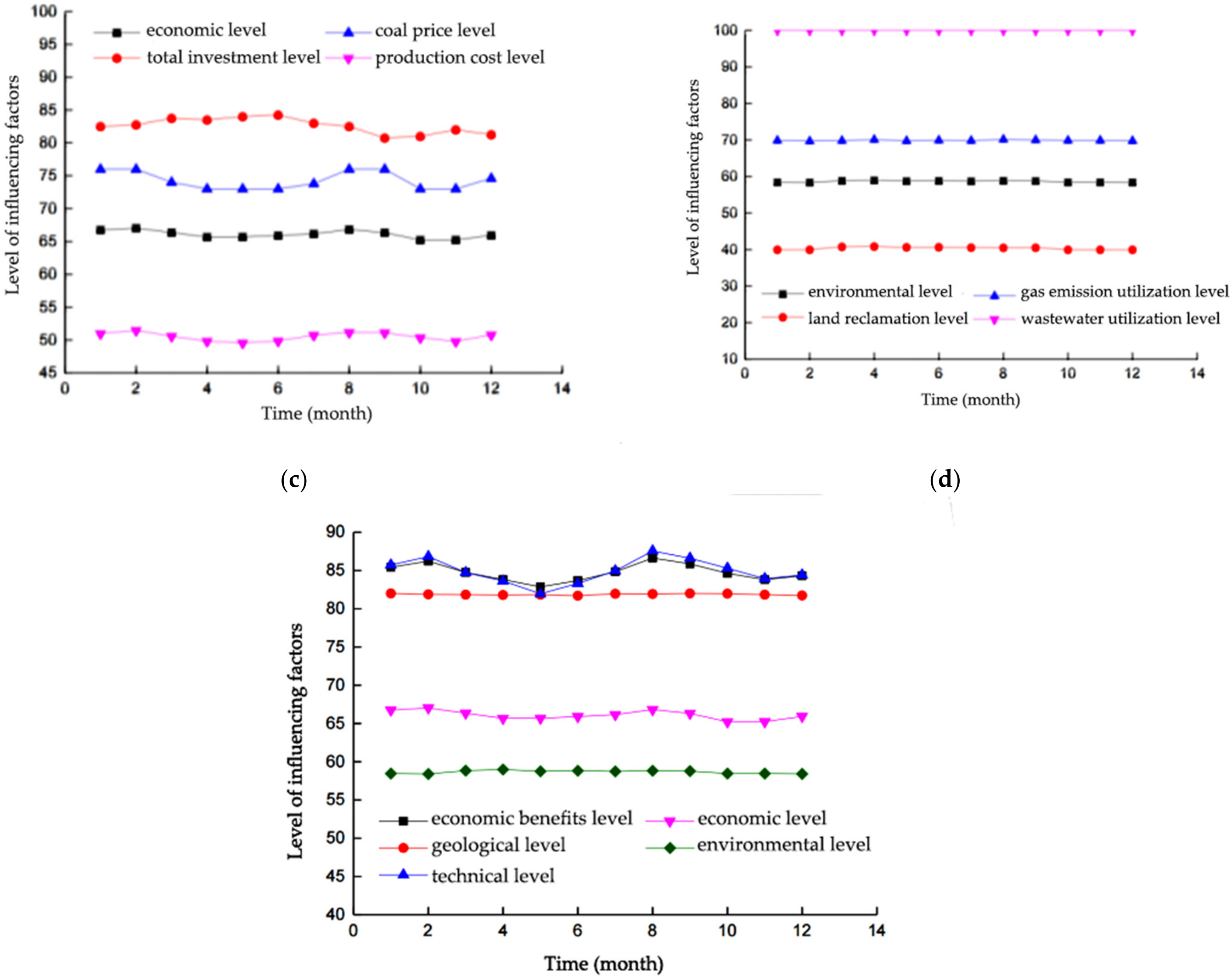
The relationship between the level of each influencing factor and the level of economic benefits is shown in Figure 6.

As seen in Figure 6e, the level of each influencing factor and the level of economic benefits show dynamic changes. The relationship between the level of each influencing factor and the level of economic benefits can be seen in that the factors that mainly affect the economic benefits are technology and the economy, and the geological and environmental factors have less influence on the economic benefits. As seen in Figure 6b, the dynamic trend in the coal production level and gas production level are the same as the trend in the technology levels. It shows that both the coal production level and the gas production level are the main factors affecting the technology level. As seen in Figure 6c, the coal price and production level are the main factors affecting the economy. The higher the coal price, the better the financial economics. The higher the production cost level and the lower the production cost, the better the financial economics. The coal price is influenced by the market and policy. It cannot be subjectively controlled. Therefore, while ensuring safe production, appropriately reducing production costs and increasing the coal extraction and gas extraction rates can help to improve the level of economic benefits.



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

(**e**)

Figure 6. (**a**) Geological factors; (**b**) Technical factors; (**c**) Economic factors; (**d**) Environmental factors; (**e**) Relationship between the level of each influencing factor and the level of economic benefits.

From the analysis of its simulation data in Figure 6e, it can be obtained that the level of economic benefits in May is lower compared to other months. The technical level of May is at the lowest level among the 12 months. In conclusion, the mining techniques such as coal extraction rate and gas extraction rate can be used to improve the technology level to achieve better economic benefits.

The relationship between the influencing factors related to the safety level and its relationship is shown in Figure 7.

From Figure 7, it can be seen that the level of each influencing factor and the safety level show dynamic changes. All influencing factors have an impact on safety levels. Of these, the integrity of the electrical and mechanical equipment and the return airflow gas concentration has a greater degree of influence on the safety level. The higher the integrity rate of the electrical and mechanical equipment, the higher the safety during the mining process, which will ensure the safety of the coal and gas co-mining production process. The higher the level of return airflow gas, the lower the concentration of return airflow gas and the higher the safety level. Therefore, the following measures are taken to ensure the safe production of coal and gas co-mining. First, the performance of electromechanical equipment by strengthening capital investment is guaranteed. The second point involves the strengthening of the frequency of personnel maintenance to improve the intact rate of electromechanical equipment. Thirdly, reduce the concentration of gas in the return stream during the mining process through ventilation and extraction.

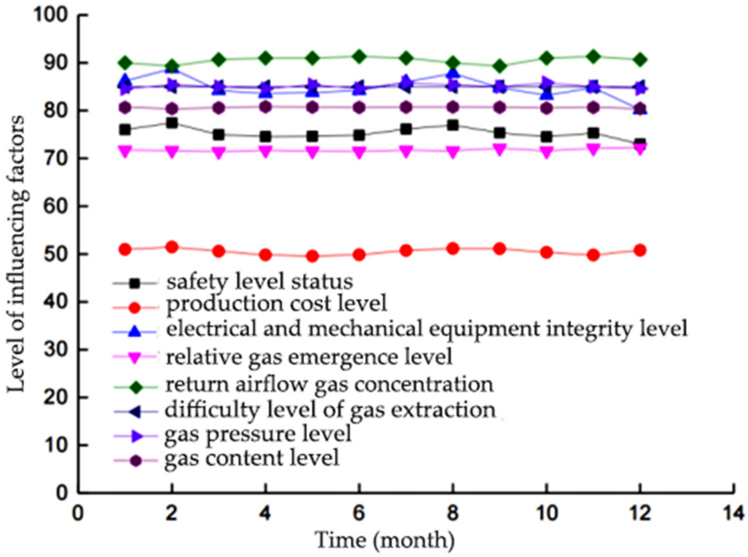


Figure 7. Relationship between the level of each influencing factor and the state of the safety level.

From the analysis of its simulation data in Figure 7, the safety level in December is lower compared with other months, in which the mechanical and electrical equipment completeness rate is at the lowest level of the 12 months. In summary, we can improve the integrity of electrical and mechanical equipment by strengthening the financial investment and frequency of personnel maintenance. Ultimately, the safe production of coal and gas co-mining is ensured.

3.2.3. Discussion

At present, the commonly used evaluation methods mainly include the hierarchical analysis method, fuzzy comprehensive evaluation method, grey comprehensive analysis method, etc. [29–31] The common feature of these methods is that they can only reflect the overall level of the evaluated object at a certain point in time but cannot reflect the influence relationship between the index and related factors within a certain time range, as well as the evolution trend of the index over time. The coal production process is always changing and dynamic evaluation is more in line with the needs of actual production. System dynamics, as a research method that integrates systems theory, cybernetics, and information theory, provides insight into current non-linear and time-varying phenomena and offers the possibility of evaluating complex systems. Therefore, the evaluation of coal and gas co-mining by introducing system dynamics is a topic worthy of further study.

4. Conclusions

In this paper, the coordination degree of the coal and gas co-mining system in the Zhuxianzhuang coal mine was simulated and evaluated. The main findings are as follows:

(1) Taking the Zhuxianzhuang coal mine as an example, the dynamic model of the coordination degree of the coal and gas co-mining system was established. The average co-mining coordination degree of the Zhuxianzhuang coal mine is 0.790. The coordination degree of this co-mining system is on the good side of coordination.

(2) The economic benefits and safety levels of the coal and gas co-mining system were analyzed based on the results of the simulation analysis subsystem. We compared the dynamic trend graphs of the two subsystems and their influencing factors and screened the main influencing factors that affect the degree of coordination of coal and

gas co-mining. We then suggested relevant opinions for the coordinated operation of the coal and gas co-mining system in the mine area.

(3) The reasonableness and practicality of the system dynamics model for the coordination degree of the coal and gas co-mining system were verified. The results show that the system dynamics model can effectively simulate the dynamic changes of different variable factors in the co-mining system.

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References

1. Hu, Z.J.; Liu, R.; Chen, Z. Strategic Thinking on the Ecological Development of Technology Under China's "Carbon Neutrality" Commitment. *Forum Sci. Technol. China* **2021**, *5*, 14–20. [CrossRef]
2. Liu, W.G.; Xu, X.; Han, J.Y.; Wang, W.; Li, Z.; Yan, Y. Trend model and key technologies of coal mine methane emission reduction aiming for the carbon neutrality. *J. China Coal Soc.* **2022**, *47*, 470–479. [CrossRef]
3. Ren, S.H.; Xie, Y.C.; Jiao, X.M.; Xie, H.P. Characteristics of Carbon Emissions During Coal Development and Technical Approaches for Carbon Neutral Development. *Adv. Eng. Sci.* **2022**, *54*, 60–68. [CrossRef]
4. Xie, H.P.; Wu, L.X.; Zheng, D.Z. Prediction on the energy consumption and coal demand of China in 2025. *J. China Coal Soc.* **2019**, *44*, 1949–1960. [CrossRef]
5. Liang, M.C.; Qin, Y.Y.; Fan, X.; Gao, X. Interpretation of the Main Conclusions and Suggestions of IPCC AR6 Working Group III Report. *Environ. Prot.* **2022**, *50*, 72–76. [CrossRef]
6. Markevych, K.; Maistro, S.; Koval, V.; Paliukh, V. Mining sustainability and circular economy in the context of economic security in Ukraine. *Min. Miner. Depos.* **2022**, *16*, 101–113. [CrossRef]
7. Yuan, L.; Zhang, N.; Kan, J.G.; Wang, Y. The concept, model and reserve forecast of green coal resources in China. *J. China Univ. Min. Technol.* **2018**, *47*, 1–8. [CrossRef]
8. National Bureau of Statistics of China. Statistical Communiqué of the People's Republic of China on the 2021 National Economic and Social Development. *China Stat.* **2022**, *3*, 9–26. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=ZGTJ202203003&DbName=DKFX2022 (accessed on 20 September 2022).
9. Xie, H.P.; Zhou, H.W.; Xue, D.J.; Gao, F. Theory, technology and engineering of simultaneous exploitation of coal and gas in China. *J. China Coal Soc.* **2014**, *39*, 1391–1397. [CrossRef]
10. Dzhioeva, A.K.; Brigida, V.S. Spatial non-linearity of methane release dynamics in underground boreholes for sustainable mining. *J. Min. Inst.* **2020**, *245*, 522–530. [CrossRef]
11. Brigida, V.S.; Zinchenko, N.N. Methane release in drainage holes ahead of coal face. *J. Min. Sci.* **2014**, *50*, 60–64. [CrossRef]
12. Qin, B.; Shi, Z.S.; Hao, J.F.; Ye, D.L.; Liang, B.; Sun, W.J. Analysis of the Space–Time Synergy of Coal and Gas Co-mining. *ACS Omega* **2022**, *7*, 13737–13749. [CrossRef]
13. Yuan, L.; Guo, H.; Shen, B.T.; Qu, Q.D.; Xue, J.H. Circular overlying zone at longwall panel for efficient methane capture of multiple coal seams with low permeability. *J. China Coal Soc.* **2011**, *36*, 357–365. [CrossRef]
14. Yuan, L. Theory of pressure-relieved gas extraction and technique system of integrated coal production and gas extraction. *J. China Coal Soc.* **2009**, *34*, 1–8.
15. Li, X.S.; Peng, J.; Xie, Y.L.; Li, Q.H.; Zhou, T.; Wang, J.W.; Zheng, W.B. Influence of High-Temperature Treatment on Strength and Failure Behaviors of a Quartz-Rich Sandstone under True Triaxial Condition. *Lithosphere* **2022**, *2022*, 3086647. [CrossRef]
16. Wang, F.; Zhang, C.; Liang, N. Gas Permeability Evolution Mechanism and Comprehensive Gas Drainage Technology for Thin Coal Seam Mining. *Energies* **2017**, *10*, 1382. [CrossRef]
17. Xie, H.P.; Gao, F.; Zhou, H.W.; Cheng, H.M.; Zhou, F.B. On theoretical and modeling approach to mining-enhanced permeability for simultaneous exploitation of coal and gas. *J. China Coal Soc.* **2013**, *38*, 1101–1108. [CrossRef]

18. Cheng, Z.H.; Chen, L.; Zou, Q.L.; Wang, H.B.; Pu, S.J.; Qi, Q.X.; Liang, C.H.; Fan, S.W.; Su, S.L.; Yan, D.H. Study on high-efficiency co-mining technology system of coal and gas in contiguous seams: A case study of Shaqu Mining Area in Lüliang, Shanxi Province. *Coal Sci. Technol.* **2021**, *49*, 122–137. [CrossRef]
19. Liang, B.; Qin, B.; Sun, F.Y.; Wang, Y.; Sun, Y.N.; KHUONG, P. Application of evaluation index system of coal and gas co-extraction and evaluation model. *J. China Coal Soc.* **2015**, *40*, 728–735. [CrossRef]
20. Forrester, J.W. Industrial Dynamics. *J. Oper. Res. Soc.* **1997**, *48*, 1037–1041. [CrossRef]
21. Jiang, Q.X.; Zhao, Y.Z.; Wang, Z.L.; Fu, Q.; Zhou, Z.M.; Wang, T. Predicting and Evaluating the Water and Soil Resources Security Risk Based on System Dynamics and Variable Fuzzy. *J. Basic Sci. Eng.* **2018**, *26*, 780–792. [CrossRef]
22. Zhou, Z.L.; Cheng, Y.; Kou, T.; Guo, P.C. Air penetration combat forces plan evaluation method based on two-stage DEA model. *Syst. Eng. Electron.* **2018**, *40*, 797–804. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=XTYD201804013&DbName=CJFQ2018 (accessed on 2 September 2022).
23. Sun, S.P.; Liu, F.L.; Xue, S. Comprehensive evaluation system for contribution degree of demand-side resources to renewable energy source integration. *Electr. Power Autom. Equip.* **2015**, *35*, 77–83. [CrossRef]
24. Yafei, W. Evaluation system construction of health policy based on system dynamics and complex network. *Clust. Comput.* **2019**, *22*, 4589–4596. [CrossRef]
25. Nguyen, T.; Cook, S.; Ireland, V. Application of System Dynamics to Evaluate the Social and Economic Benefits of Infrastructure Projects. *Systems* **2017**, *5*, 29. [CrossRef]
26. Lu, W.D.; Cheng, G.; Liu, J.; Li, X.C. Based on GAHP-BOCR Coal and Gas Simultaneous Extraction Decision Analysis. *Coal Technol.* **2017**, *36*, 146–149. [CrossRef]
27. Sherin, S.; Rehman, Z.; Hussain, S.; Mohammad, N.; Raza, S. Hazards identification and risk analysis in surface mines of Pakistan using fault tree analysis technique. *Min. Miner. Depos.* **2021**, *15*, 119–126. [CrossRef]
28. Kobylianskyi, B.; Mykhalchenko, H. Improvement of safety management system at the mining enterprises of Ukraine. *Min. Miner. Depos.* **2020**, *14*, 34–42. [CrossRef]
29. Zhong, S.H.; Jiang, X.D. Mining Mode Selection of Coal and Gas Simultaneous Mining Based on FAHP. *Coal Eng.* **2015**, *47*, 87–89. Available online: https://kns.cnki.net/kcms/detail/11.4658.TD.20151020.0948.056.html (accessed on 3 August 2022).
30. Liu, X.L.; Zhang, Z.Y. Risk analysis of coal and gas outburst using gray comprehensive evaluation. *J. Liaoning Tech. Univ. Nat. Sci.* **2012**, *31*, 609–612. Available online: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=FXKY201205009&DbName=CJFQ2012 (accessed on 3 August 2022).
31. Xu, E.Y.; Li, X.J.; Xue, F. Assessment of coal and gas outburst by AHP-GT combined model. *Saf. Coal Mines* **2022**, *53*, 172–177. [CrossRef]