Innovation and Application of Cooperative Management Mechanism of Progress and Cost of Oil and Gas Exploration and Development Projects

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Abstract

Aiming at the inefficiency caused by the separation of schedule and cost control in oil and gas exploration and development projects, a dynamic collaborative management mechanism based on digital twinning and deep reinforcement learning (DRL) is constructed in this study. Through system dynamics modeling, it reveals the dynamic influence of key coupling variables such as geological risk index and engineering complexity on schedule and cost, and puts forward a management framework of "three-layer linkage and dynamic closed loop": using the digital twin platform integrated with Internet of Things and BIM to realize real-time correction of geological risks; The deep Q network (DQN) is used to solve the multi-objective optimal scheduling strategy. Establish a closed-loop process of "early warning-negotiation-adjustment-learning" to improve the management synergy coefficient. Taking Block Y of X Oilfield as an example, after implementation, the project duration was shortened by 2.4 months, the cost overrun rate was reduced by 20.9%, and the inter-departmental decision-making period was shortened to 1.5 days, which verified the remarkable effect of this mechanism in unconventional oil and gas field projects and provided a reusable technical path for project collaborative management under complex geological conditions.

Keywords

Exploration and Development of Oil and Gas Fields; Cost Collaborative Management; Digital Twins; Deep Reinforcement Learning.

1. Introduction

As the core link of energy industry, oil and gas field exploration and development has the typical characteristics of large investment scale, high technical complexity and long construction period [1]. Under the traditional management mode, the disadvantages of separate control of schedule and cost are increasingly prominent. At present, the industry is still dominated by "island-like" information systems, and the cross-departmental data sharing rate is insufficient, resulting in a decision-making response cycle of several weeks, which is difficult to meet the agile management needs under the fluctuation of oil prices [2]. With the acceleration of global energy transformation, oil and gas enterprises are facing the dual pressures of "double carbon" goal and reducing costs and increasing efficiency [3]. In this context, the construction of dynamic collaborative management mechanism of schedule and cost has become the key path for the industry to break through the bottleneck of development.

This study breaks through the research paradigm of "binary separation" between schedule and cost in traditional project management, and brings geological uncertainty, engineering complexity and management synergy into a unified analysis framework for the first time, and establishes a dynamic coupling model based on digital twins to fill the gap in the theory of multi-factor collaborative management under complex geological conditions. The dynamic coupling relationship between schedule, cost and geological risk is revealed through system dynamics modeling. Develop a multi-objective optimization algorithm based on deep reinforcement learning (DRL) to solve the decision-making problem under nonlinear constraints; Build a collaborative management platform that integrates Internet of Things, BIM and digital twins to realize data-driven management in the whole life cycle.

2. Progress-cost Synergy Mechanism Analysis of Oil and Gas Field Projects

In oil and gas field exploration and development projects, there is a typical "mutually exclusive-symbiotic" relationship between schedule and cost [4]. Accelerating the schedule usually requires an increase in resource input, but if the schedule is delayed, it may lead to cost overruns due to equipment leasing and personnel waiting for work [5]. The core of collaborative mechanism analysis is to identify the key variables and feedback loops of their dynamic coupling. Identification of key coupling variables is shown in Table 1.

Table 1. Identification of key coupling variables

Key coupling variable	Symbol	Definition description
Geological risk index	$R_g(t)$	Reflect the uncertainty of underground structure and reservoir physical properties, and affect drilling speed and completion scheme
Engineering complexity	$C_e(t)$	Comprehensive measurement of technical parameters such as well type, well depth and number of fracturing sections
Elasticity of resource allocation	$E_r(t)$	Adjustable ability of manpower, equipment and materials
Management synergy coefficient	$\gamma(t)$	Cross-departmental information sharing and decision-making synchronization level

Based on system dynamics, the coupling equation of schedule deviation rate $S(t)$ and cost deviation rate $P(t)$ is defined as:

$$\begin{cases} \dfrac{dS(t)}{dt} = \alpha_1 v(t) - \beta_1 R_g(t) - \gamma(t)\delta P(t) \\ \dfrac{dP(t)}{dt} = \alpha_2 u(t) + \beta_2 R_g(t) + \gamma(t)\delta S(t) \end{cases} \tag{1}$$

Where $S(t)$ is the difference between the planned progress completion rate and the actual progress completion rate; $P(t)$ is the difference between the budgeted cost and the actual cost divided by the budgeted cost, and a positive value indicates overspending; $v(t)$ is the actual working speed; $u(t)$ is the input intensity of resources per unit time; α_1, α_2 is the technical efficiency coefficient, which is obtained by regression of historical data; β_1, β_2 is the sensitivity coefficient of geological risk, ranging from 0.2 to 0.8. The higher the risk, the greater the value. δ is a cross-influence factor, which reflects the transmission intensity of schedule deviation to cost, and usually takes 0.3~0.5.

The equation reveals that geological risk is the common driving force of schedule and cost fluctuation, and the management synergy coefficient $\gamma(t)$ is the only "shock absorber" that can be actively adjusted-when information sharing is timely (γ is close to 1), the negative coupling between schedule and cost can be effectively suppressed.

3. Innovative Design of Collaborative Management Mechanism

Based on the above mechanism, a collaborative management mechanism of "three-layer linkage and dynamic closed loop" is designed (as shown in Figure 1).

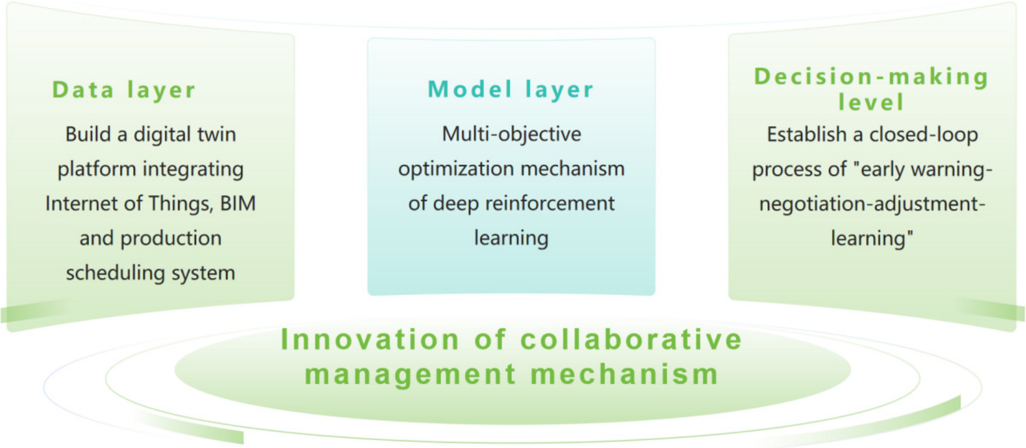

Figure 1. Collaborative management mechanism of "three-layer linkage and dynamic closed loop"

(1) Real-time sensing mechanism driven by digital twins (data layer)

Build a digital twin platform integrating Internet of Things (well site sensors, drilling rig parameters), BIM (geological model, wellbore structure) and production scheduling system. The key innovation lies in the dynamic updating algorithm of geological risk;

$$R_g(t+1)=R_g(t)e^{-\lambda\Delta H}+\left(1-e^{-\lambda\Delta H}\right)\frac{\sum w_i x_i(t)}{N} \tag{2}$$

Where ΔH is the newly added drilling footage; λ is the information attenuation coefficient, with a value of 0.01~0.05, indicating that the uncertainty of initial geological assumptions decreases with the deepening of drilling; $x_i(t)$ is the i real-time monitoring parameter; w_i is the weight of each parameter, which is determined by random forest [6]. This formula can automatically correct the geological risk prediction value with the progress of the project, and provide more accurate input for the schedule-cost collaborative optimization.

(2) Multi-objective optimization mechanism of DRL (model layer)

The collaborative decision-making of schedule and cost is modeled as markov decision processes, and the optimal scheduling strategy is solved by deep Q network (DQN) [7-8]. The optimization objective function is:

$$\min_{a_t}\left[\omega_1\frac{P(t)}{P_{\max}}+\omega_2\frac{S(t)}{S_{\max}}+\omega_3 E\left[R_g(t+1)\right]\right] \tag{3}$$

In the above formula, a_t is the decision-making action at t moment, such as increasing/decreasing the number of drilling rigs, adjusting drilling fluid system and modifying the number of fracturing sections. $\sum\omega_i=1$ is the weight coefficient, which satisfies cc and can be dynamically adjusted according to oil price fluctuation. When the oil price is high, reduce ω_2 to give priority to the schedule. $P_{\max}, S_{\max}$ is the maximum allowable cost overrun rate and schedule lag rate of the project. $E\left[R_g(t+1)\right]$ is the expected value of geological risk in the next stage based on the current data prediction. Constraints include total resource limitation, technical feasibility and red line of safety and environmental protection.

(3) Dynamic coordinated regulation mechanism (decision-making layer)

Establish a closed-loop process of "early warning-negotiation-adjustment-learning". When $S(t) > 0.1$ or $P(t) > 0.08$ triggers a yellow warning, it needs to be negotiated by the department; If it exceeds 0.2/0.15, a red warning will be triggered, which requires the intervention of the project director. Shapley value method is used to allocate the extra cost and schedule income brought by resource adjustment, so as to avoid the deadlock in the game of "pressing the schedule of oil production plant and ensuring the cost of drilling team". After the DQN model outputs a_t, the three steps of "simulation-evaluation-confirmation" are carried out through the digital twin platform to ensure the feasibility of the adjustment scheme. After each actual execution, ($S(t), P(t), a_t$, actual result) is stored in the experience pool, and the DQN model is retrained offline every 500 decision steps.

4. Application Case Study

Block Y of X Oilfield is a typical low permeability sandstone reservoir. It is planned to complete the drilling and completion of 15 horizontal wells and ground supporting projects within 12 months, with a total budget of 820 million yuan. In the first three months after the start of the project, the traditional "schedule-cost split-track management" mode was adopted, and the updating of geological modeling was delayed. In the second month, two wells were sidetracked due to faults, and the non-production time increased by 22 days. In order to catch up with the lagging progress, the drilling team blindly increased the penetration rate, causing wellbore instability, and the additional treatment cost was 6.8 million yuan; The average decision-making period of oil production plant and drilling company is 12 days due to poor coordination of resource allocation (drilling rig and fracturing truck set).

Table 2. Changes of key indicators (4th to 12th month)

Time (month)	Progress deviation rate	Cost deviation rate $P(t)$	Geological risk index $R_g(t)$	Management synergy coefficient $\gamma(t)$
3 (before intervention)	0.18	0.14	0.67	0.32
4	0.16	0.12	0.58	0.51
5	0.11 $S(t)$	0.09	0.49	0.63
6	0.07	0.06	0.41	0.72
7	0.04	0.04	0.35	0.76
8	0.02	0.02	0.30	0.79
9~12	-0.01~0.01	0.00~0.02	0.22~0.28	0.77~0.81

Note: A negative value of $S(t)$ indicates that it is ahead of schedule.

Evaluation of the project at the end of March: the progress lag rate is $S = 0.18$, the planned completion rate is 30%, but the actual completion rate is only 25%, the cost overrun rate is $P = 0.14$, and the actual expenditure is 137 million yuan vs the budget is 120 million yuan. Then the progress-cost collaborative management mechanism of this study is introduced. 433 IoT sensors (vibration, torque, mud flow, gas composition) were deployed on 6 drilling rigs and 3 fracturing platforms, and the data were synchronized to the BIM geological model every 15 minutes. Using formula (2), $\lambda = 0.03$ and w_i are obtained from random forest training, and the top three weights are drilling time 0.42, gas logging total hydrocarbon 0.31 and gamma 0.18. The state space includes [$S(t), P(t), R_g(t)$, number of remaining wells, resource availability rate], and the action space includes seven scheduling strategies, such as adding a drilling rig, reducing the penetration rate by 5% to protect the borehole wall, and rearranging the fracturing sequence. The reward function is set to $r = -\lfloor 0.4P(t) + 0.4S(t) + 0.2R_g(t) \rfloor$. A daily early warning consultation mechanism is established to increase the management synergy coefficient $\gamma(t)$ from 0.32 to 0.79. Changes of key indicators (4~12 months) are shown in Table 2.

During the 4th to 12th months after the implementation of the intervention measures, the key indicators of the project continued to improve: The progress deviation rate $S(t)$ is reduced from 0.16 to -0.01~0.01 (negative value means that the progress is ahead of schedule), the cost deviation rate $P(t)$ is reduced from 0.12 to 0.00~0.02, the geological risk index $R_g(t)$ is significantly reduced from 0.58 to 0.22~0.28, and the management synergy coefficient $\gamma(t)$ is greatly increased from 0.51 to 0.77~0.81, which shows that the project is in progress, cost control and management coordination.

Figure 2 shows the movement trajectory of the project on the "cost deviation-schedule deviation" plane before and after the intervention. In the first three months, the trajectory drifted to the upper right, the schedule lag was aggravated and the cost overrun was enlarged; From the fourth month, the trajectory turned to the lower left, and the convergence speed accelerated month by month; After the eighth month, it entered the stable region ($|S| < 0.02, |P| < 0.02$) near the origin, and achieved "quasi-zero deviation" collaboration.

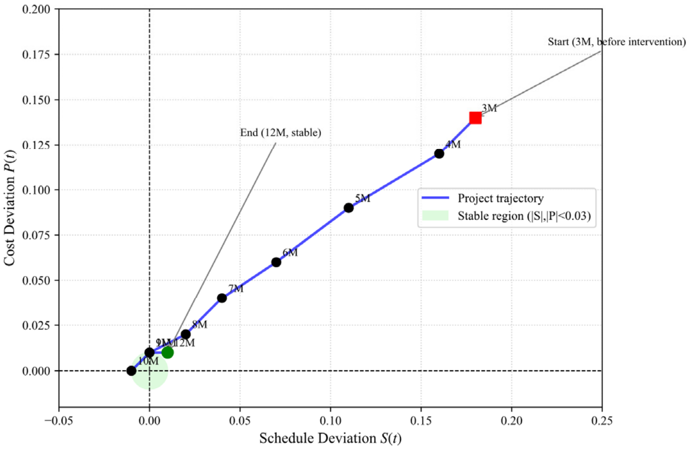

Figure 2. Cost-schedule collaborative trajectory diagram

In the 5th and 5th month, when the well A3 was drilled to 3400 meters, the real-time $R_g(t)$ jumped from 0.41 to 0.63, and the gas logging was abnormal and the drilling time suddenly increased. The report of traditional mode → geological study (3 days) → decision of sidetracking or stopping drilling, with an estimated cost increase of 3.8 million yuan and a schedule loss of 7 days. Under the response of collaborative mechanism, the digital twin platform completes 100 Monte Carlo simulations in 2 minutes, and predicts the $\Delta P, \Delta S$ of three schemes (stopping drilling/slowing down/maintaining the original speed); DQN model recommends "reducing speed by 20%+ increasing mud proportion", and outputs the expectation that the progress will be lost by 1.8 days and the cost will be increased by 550,000 yuan; On the same day, the implementation was approved by the consultation, and the actual result lost 2.1 days and the cost was 620,000 yuan, thus avoiding a potential blowout risk. The overall benefits are shown in Table 3.

Table 3. Overall benefit

Index	Traditional mode (Extrapolating the whole year in the first three months)	Synergistic mechanism (Actual September)	Improvement range
Total project duration (month)	14.2	11.8	2.4 months in advance
Final cost overrun rate	+23%	+2.1%	Decrease by 20.9 percentage points
Non-productive time caused by geological risks	47 days	18 days	Decrease by 61.7%
Inter-departmental decision-making cycle (days)	12	1.5	Shorten by 87.5%
γ -means of management synergy coefficient	0.31	0.74	Increase by 139%

5. Conclusion

In the practical application of block Y, the progress-cost collaborative management mechanism pulls the project from the vicious circle of "lag+cost overrun" into the quasi-steady collaborative interval through dynamic geological risk quantification, DRL scheduling and consultation process with high synergy coefficient. The case verifies the engineering effectiveness of the proposed model and algorithm, and also provides a reusable implementation template for similar unconventional oil and gas field projects.

References

[1] Jing Peng. Cost Control Strategies in Cost Management During Oil and Gas Exploration [J]. Chemical Industry Management, 2026, (07): 1-4. DOI: 10.19900/j.cnki.ISSN1008-4800.2026. 07. 001.

[2] Zhang Meng. A Discussion on Cost Control in Southwest Oil and Gas Field Enterprises [J]. Cooperative Economy and Technology, 2023, (06): 138-140. DOI: 10.13665/j. cnki.hzjjykj. 2023. 06. 009.

[3] Chen Wenqi. A Study on Cost Management Issues in Oil and Gas Enterprises: A Case Study of Company Y [J]. Modern Industrial Economy and Information Technology, 2024, 14(01): 206-208. DOI: 10.16525/j.cnki.14-1362/n.2024.01.064.

[4] Zhang Xinning. Research on the Current Status and Countermeasures of Cost Management in China’s Oil and Gas Enterprises [J]. Finance and Economics, 2023, (13): 78-80. DOI: 10. 19887 /j. cnki. cn11-4098/f.2023.13.035.

[5] Zou Kaiping. Cost Control and Cost Management in Oil and Gas Pipeline Engineering [J]. Chemical Industry Management, 2023, (07): 7-9. DOI: 10.19900/j.cnki.ISSN1008-4800.2023.07.003.

[6] Wang Haiyu, Qu Boyang, Qiao Baihao. Multi-objective Economic Statistical Optimization Design of Cumulative and Control Charts Considering Monitoring Costs and Efficiency [J]. Mathematical Statistics and Management, 2021, 40 (05): 761-770. DOI:10.13860/j.cnki.sltj.20201219-012.

[7] Yang Guosen, Xie Xiangsheng. Multi-objective Risk Decision-Making for Engineering Projects Considering Risk Correlation [J]. Journal of Civil Engineering and Management, 2017, 34 (06): 159-164. DOI:10.13579/j.cnki.2095-0985.2017.06.026.

[8] Rong Chuitian, Tian Haohui, Du Fang. Multi-objective Deep Reinforcement Learning-Driven Parameter Optimization Technique for Database Systems [J]. Journal of Software, 2025, 36 (12): 5512-5536. DOI:10.13328/j.cnki.jos.007405.