Research on Multi-objective Collaborative Scheduling and Risk Assessment Method of Urban Underground Pipe Network

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Abstract: With the continuous expansion of city scale, the complexity of underground pipe network system also increases, and the single system independent operation mode can no longer meet the needs of smart cities. In this paper, a multi-objective collaborative scheduling and risk assessment method of urban underground pipe network integrated with "modeling-evaluation-optimization" is proposed to solve the problems of low resource utilization efficiency and difficulty in coping with extreme weather events and compound disasters in traditional models. Firstly, based on the complex network theory, a multi-pipe network coupling model is constructed to describe the physical and functional relationship between systems. Then the dynamic load-capacity model is used to simulate the fault cascade process, quantify the risk propagation path and evaluate the system resilience. Then, a four-dimensional collaborative optimization model of "efficiency-safety-economy-environment" is established, and the adaptive optimization of scheduling strategy is realized by combining with deep reinforcement learning (DRL). Finally, BIM+GIS and digital twin technology are combined to construct virtual mapping of pipe network, and realize three-dimensional visualization, real-time data mapping and simulation decision verification of pipe network system. Through case analysis, it is verified that this method can effectively curb the expansion of faults, improve the overall toughness of urban lifeline system, and provide scientific basis for decision makers.

1. Introduction

The traditional mode of "single system running independently" leads to low efficiency of resource utilization, and it is difficult to cope with the challenges brought by extreme weather events and compound disasters caused by climate change. Although the investment in smart cities is increasing all over the world, the existing research and technology are mostly focused on the optimization and local monitoring of a single pipe network, and lack of in-depth discussion on the dynamic coupling relationship between multiple pipe networks and the risk propagation law, which can not meet the comprehensive needs of smart cities [1].

This study breaks through the limitations of traditional single-objective optimization and expands the application of multi-objective optimization theory in the field of urban infrastructure by constructing a four-dimensional cooperative scheduling model of "efficiency-safety-economy-environment". Based on the complex network theory, the cascade propagation mechanism of faults between multi-pipe networks such as drainage and electric power is revealed quantitatively, which provides theoretical support for system toughness evaluation. Combining BIM+GIS and digital twin technology to construct virtual mapping of pipe network, and introducing deep reinforcement learning (DRL) learning to realize adaptive optimization of dispatching strategy, so as to promote the development of urban lifeline system simulation and intelligent decision theory.

2. Overall frame design

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Put forward an integrated framework of "modeling-evaluation-optimization", as shown in Figure 1. Through the complex network theory, the coupling model of drainage, electricity, gas and other multi-pipe networks is constructed to depict the physical and functional relationship between the systems. The dynamic load-capacity model is used to simulate the fault cascade process, quantify the risk propagation path and evaluate the system toughness [2]; A four-dimensional collaborative optimization model of "efficiency-safety-economy-environment" is established, and the dynamic generation of scheduling strategy is realized by combining DRL. Finally, BIM+GIS technology is integrated to build a digital twin platform, which realizes three-dimensional visualization, real-time data mapping and simulation decision verification of the pipe network system, and forms a complete technical system integrating modeling, evaluation, optimization and visualization.

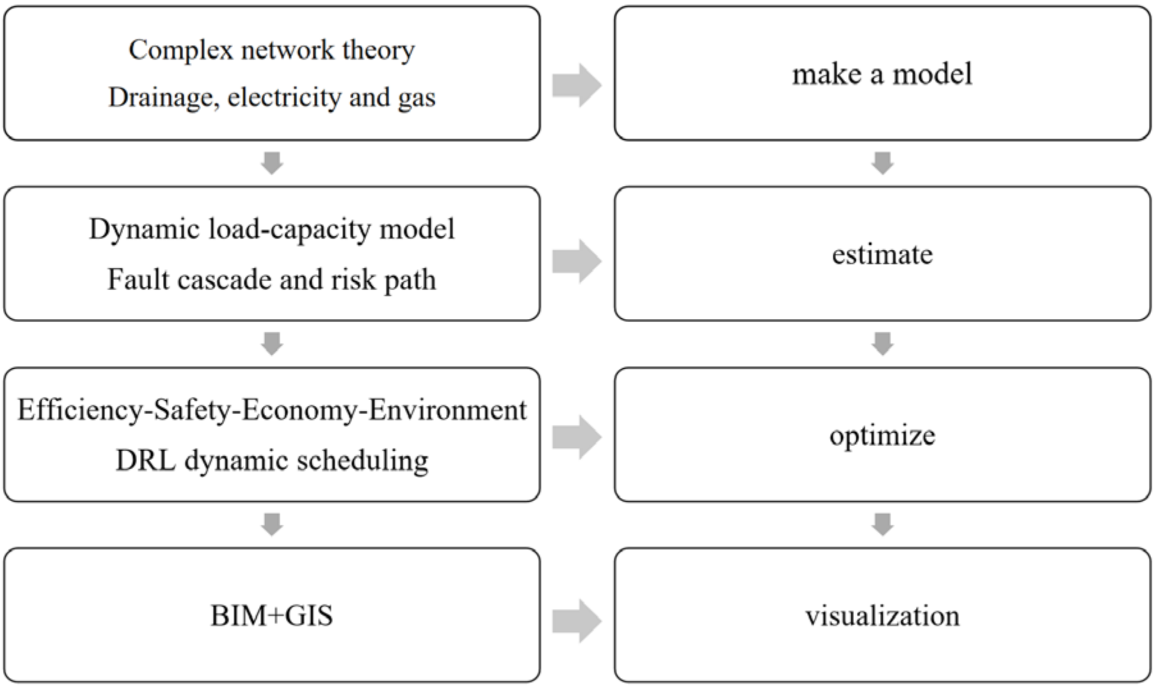

Figure 1 Integrated framework of "modeling-evaluation-optimization"

3. Key method

3.1 Multi-official website coupling modeling

The coupled modeling of multi-pipe network system is carried out by using directed weighted graph, in which nodes represent key facilities such as pumping stations, substations and valves, and have attributes such as type, capacity and load. The edge represents the connection relationship of pipelines and cables, and the weight reflects the flow or energy transmission capacity and dependence strength [3]; By introducing cross-system edge and incidence matrix C_{ij} (representing the dependence of system i on system j), the physical and functional coupling relationship between different pipe networks such as electricity, drainage and gas is described.

3.2 Quantitative model of risk propagation

Load-capacity cascade failure model is used to simulate fault propagation [4-5]. Initial load $L_i(t)$ and capacity $\Gamma_i = (1+\alpha)L_i(0)$($\alpha \geq 0$ is the fault tolerance coefficient). When a node fails, its load is redistributed to neighboring nodes in proportion, triggering cascade effect. Node failure conditions are:

$$L_i(t) > \Gamma_i \quad (1)$$

The system toughness index R is defined as the performance retention ratio after failure recovery:

$$R = \frac{\sum_{i \in S} L_i(T_{end})}{\sum_{i \in S} L_i(0)} \quad (2)$$

Where S is the set of system nodes and T_{end} is the end time of simulation.

3.3 Multi-objective collaborative scheduling model

Constructing a four-dimensional optimization objective function:

$$\min F(x) = \left[- f_{efficiency}(x), f_{risk}(x), f_{cost}(x), - f_{environment}(x)\right]^T \quad (3)$$

Where x is the decision variable; $f_{efficiency}$ is the throughput efficiency of the pipe network; f_{risk} is the system risk index; f_{cost} is the economic cost of dispatching operation; $f_{environment}$ is environmental benefit.

Constrained weighted sum is used to deal with multi-objective optimization, and weight vector $w = [w_1, \cdots, w_4]$ is introduced to reflect the priority of each dimension:

$$F^{'}(x) = \sum_{k=1}^{4} w_k \tilde{f}_k(x) \quad (4)$$

Where $\tilde{f}_k$ is the normalized objective function.

3.4 Adaptive optimization based on DRL

The adaptive optimization method based on deep Q-network (DQN) is used to learn the dynamic scheduling strategy to realize the efficient, low-risk, low-cost and environment-friendly operation of the pipe network system [6]. State space consists of real-time state of pipe network, including node load, fault information and environmental data. The action space covers dispatching operations such as adjusting pump speed and switching power lines.

The reward function is designed by integrating multi-objective weights in the form of:

$$r_t = -\left[w_1 \Delta f_{eff} + w_2 \Delta f_{risk} + w_3 \Delta f_{cost} - w_4 \Delta f_{env}\right] \quad (5)$$

Encourage the system to perform operations with excellent performance in efficiency improvement, risk reduction, cost control and environmental protection.

4. Empirical research and case analysis

4.1 Case background and scene setting

The study selects the area of about 25 square kilometers in the High-tech Zone of A City as a case. The underground pipe network in this area is dense, covering rainwater drainage, electricity and gas systems, and the coupling between the systems is close. For example, the drainage pumping station depends on electricity supply and the substation is easily affected by flooding. Simulate the torrential rain scene caused by typhoon "Meihua", which lasts for 24 hours and the maximum hourly rainfall reaches 60 mm/h (once in 50 years). The rainstorm causes the 110kV substation (labeled Sub-A) in low-lying areas to trip due to the surrounding water flowing backwards and the cable layer is flooded. As the initial fault event, the analysis and verification of multi-pipe network coupling risk propagation and coordinated dispatching are carried out.

4.2 Model construction and input

Based on the BIM+GIS data provided by City A, a coupling network model with 285 key nodes (drainage pumping station, substation, switching station and gas pressure regulating station) and 420 edges (pipeline, cable and pipeline dependency) is constructed. Examples of C -part parameters of cross-system dependency matrix are shown in Table 1 below. The dispatching decision variables mainly include the start-stop and speed control of pumping stations, the contact switch switching of power grid and the load switching scheme.

Table 1 C-part parameters of cross-system dependency matrix

Dependency relationship	Dependent intensity C_{ij}	Explain
Drainage pump station _P1 → substation _Sub-B	0.95	P1 pump station is powered by Sub-B substation, which is highly dependent.
Substation _Sub-A → Gas Station _G1	0.30	The control system of G1 station is powered by Sub-A, with moderate dependence.

4.3 Simulation results and analysis

The fault cascade propagation process is simulated under two scenarios: no cooperative scheduling (traditional mode) and cooperative scheduling (this research method). In the traditional mode, after the Sub-A substation fails, its load is transferred to the adjacent Sub-B substation, which leads to the overload trip of sub-b. The power failure of Sub-B paralyzed the drainage pumping stations P1 and P2 which depended on its power supply, and the drainage capacity plummeted, which led to a wider urban waterlogging. Waterlogging has further flooded more power facilities, forming a vicious circle of "power failure-waterlogging-power failure again". In the collaborative dispatching mode, after the fault of Sub-A, the model predicts that Sub-B has overload risk through risk propagation algorithm, and immediately triggers the dispatching strategy: ① start the standby line of the power grid and transfer part of the load of Sub-B to other substations; ② Coordinate and start the standby drainage pump station P3 located in the highland, and maximize the drainage capacity of the pump station P4 that is still in operation.

The result pair is shown in Figure 2 below. The simulation results show that the collaborative scheduling strategy significantly slows down the decline of system functions, and greatly improves the resilience, and the system toughness index R is increased from 0.52 in the traditional mode to 0.85.

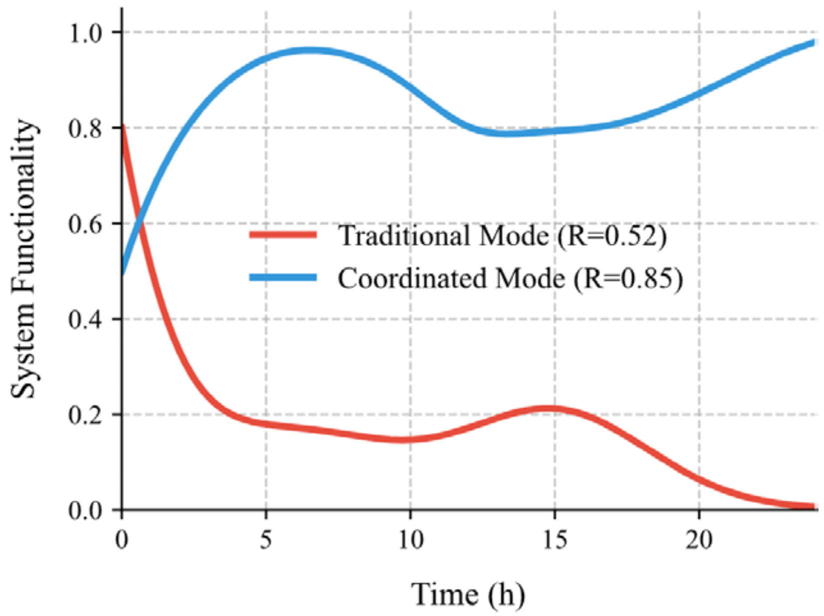

Figure 2 Risk propagation simulation results

Using the scheduling strategy trained by DRL algorithm, multi-objective optimization is realized in the 24-hour simulation period. Table 2 below is a comparison between the achievement of the four-dimensional objectives and the traditional single-objective (only maximizing drainage efficiency) scheduling scheme.

Table 2 Multi-objective performance comparison table of scheduling schemes

Performance index	Traditional single-objective scheduling scheme	In this study, collaborative scheduling scheme is proposed.	Lifting effect
Efficiency ($f_{efficiency}$)	Total drainage: 1.25 million m³	Total drainage: 1.18 million m³	-5.6%
Safety/Risk (f_{risk})	Number of final failed nodes: 38	Number of final failed nodes: 15	+60.5%
Economy (f_{cost})	Electricity fee+equipment loss: 45,000 yuan	Electricity fee+equipment loss: 38,000 yuan	+15.6%
Environment ($f_{environment}$)	Direct rainwater drainage rate: 85%	Rainwater recycling rate: 40%	(Direct discharge rate reduced to 60%)

The cooperative scheduling scheme in this study has a slight sacrifice in efficiency (reducing the water discharge by 5.6%), but it has brought about a significant reduction in safety risk (reducing the faulty nodes by 60.5%) and economic cost (reducing by 15.6%), and at the same time, it has increased rainwater recycling through intelligent storage, with remarkable environmental benefits. This reflects the value of multi-objective trade-off optimization, that is, to maximize the comprehensive benefits of the system with acceptable efficiency loss.

Faults between underground pipe networks will propagate in cascade through dependence, and the traditional "treating the head with a headache" model cannot effectively deal with them. The "multi-objective collaborative scheduling and risk assessment method" constructed in this study can quantify the risk propagation path, and effectively curb the expansion of faults in extreme weather events by adaptively optimizing the scheduling strategy, and significantly improve the overall resilience of the urban lifeline system. This method successfully realizes the collaborative optimization of the four goals of "efficiency-safety-economy-environment", which provides a scientific basis for decision makers and proves its great potential in practical application.

5. Conclusion

Aiming at the limitation of the traditional mode of "single system running independently" in dealing with extreme weather and compound disasters, a four-dimensional cooperative scheduling model of "efficiency-safety-economy-environment" is proposed, and a multi-objective cooperative scheduling and risk assessment system of urban underground pipe network is constructed by combining complex network theory, BIM+GIS technology and DRL method. The empirical study shows that the system can effectively quantify the cascading propagation mechanism of faults among multiple pipe networks, and significantly improve the overall toughness of urban lifeline systems in extreme weather events such as typhoons. Specifically, in the simulated torrential rain scene, compared with the traditional model, the collaborative scheduling strategy greatly reduces the number of failed nodes in the system (by 60.5%), improves the system toughness index (from 0.52 to 0.85), and at the same time saves the economic cost (by 15.6%) and increases the utilization rate of rainwater recovery (by 60%). Although the drainage efficiency is slightly sacrificed (reduced by 5.6%), the overall benefit is remarkable, which proves the value of multi-objective trade-off optimization. This study provides theoretical support and practical basis for scientific decision-making of urban underground pipe network, and has a wide application prospect.

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