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Research on complex networks' repairing characteristics due to cascading failure

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HIGHLIGHTS

- A repair model was built, which encompassing all the possibilities of energy transfer.
- A detailed description of the status of each repaired node can be displayed.
- A delayed opening mode was proposed to alleviate the contradiction in immediate opening.

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ABSTRACT

In reality, most of the topological structures of complex networks are not ideal. Considering the restrictions from all aspects, we cannot timely adjust and improve network defects. Once complex networks collapse under cascading failure, an appropriate repair strategy must be implemented. This repair process is divided into 3 kinds of situations. Based on different types of opening times, we presented 2 repair modes, and researched 4 kinds of repair strategies. Results showed that network efficiency recovered faster when the repair strategies were arranged in descending order by parameters under the immediate opening condition. However, the risk of secondary failure and additional expansion capacity were large. On the contrary, when repair strategies were in ascending order, the demand for additional capacity caused by secondary failure was greatly saved, but the recovery of network efficiency was relatively slow. Compared to immediate opening, delayed opening alleviated the contradiction between network efficiency and additional expansion capacity, particularly to reduce the risk of secondary failure. Therefore, different repair methods have different repair characteristics. This paper investigates the impact of cascading effects on the network repair process, and by presenting a detailed description of the status of each repaired node, helps us understand the advantages and disadvantages of different repair strategies.

1. Introduction

With the acceleration of social modernization, complex systems gradually improved but also became more and more complicated. The main method of studying complex systems involves the theory of complex networks, through which many gratifying achievements have been obtained, such as application in aeronautics and astronautics, transportation, communication, management, sociology, and other important areas [1–7]. Researching complex networks aids the design

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of optimal network structures [8–10], and with a minimal set of driver nodes we can control network transition to the desired state [11,12]. However, there are many deficiencies in real life complex networks because of the rapid development of society and the limitations of original design. These are illustrated in the following examples: the collapse of the Internet in 1986, the breakdown of North American power systems in 2003, the power network failure in southern China in 2008, and the Qingdao, China pipeline explosion in 2013. These accidents tell us a realistic truth: these networks have problems. Some researchers have addressed these problems by improving network robustness. Shargel et al. [13] studied a parameterized family of networks, optimizing the parameter values to create a novel network with an aggregate of properties superior to those of standard networks. Additionally, Gao et al. [14,15] found that in interacting networks, the node failure in 1 network generally leads to the failure of dependent nodes in other networks, which in turn may cause further damage to the first network, leading to cascading failures and catastrophic consequences. They also established a framework for interdependent networks and believed that there are many remaining challenges. Many scholars have applied the theory of complex networks to solve problems in their professional fields, and have presented many suggestions for network optimization [13–17]. However, there are many limitations in practical applications, such as economic, technology, and policy. It is not realistic to break an existing network and then rebuild, and the best method is to improve it step by step. Repair strategies can guarantee the smooth transition of the network to the security phase, and therefore, how to effectively repair damaged networks has become a more practical problem. Chi et al. [18] studied the stability of random networks in the process of constant attack and repair. Hu et al. [19] studied 3 kinds of network repair strategies, average repair, emphasis repair, and preferential repair, and analyzed the efficiency of these repair strategies under various attack strategies. However, most studies have been confined to static models, and few studies about repair strategies considered the risk of secondary failure caused by cascading effects. Compared with static models, the circumstance of a dynamic repair model is harsh and changeable, and the nodes repaired in the dynamic model can not only restore their own role but also reduce the impact of adjacent failed nodes and restore network function more effectively. Therefore, in this paper, we established a dynamic repair model and studied the relationships among network efficiency, risk of secondary failure, and additional expansion capacity caused by cascading effects under different repair strategies. We hope our research can help repair damaged networks with a more flexible strategy.

The rest of this paper is organized as follows: in Section 2 we present the failure model and repair model, and theoretically verify the possibility of secondary failure; in Section 3 we analyze the repair characteristics of immediate opening under different repair strategies; in Section 4, we study the properties of delayed opening under different repair strategies; and finally, summaries and conclusions are presented in Section 5.

2. Modeling and theoretical basis

2.1. Failure model

The classic load–capacity model [20] ($C_i = (1 + \alpha)L_i$) was presented in 2002 by Motter and Lai (ML model), and since then a large number of load–capacity models [3,21] have been built by scholars in various fields, improving the defects of the ML model. These new models can depict the transfer law in real life complex systems with more detail. For our study, we chose the nonlinear model ($C_i = \alpha + \beta L_i$), which was established by Rui [3] in 2008, where α and β are tunable parameters. The initial load [22] of node i is correlated with its link degree k as $L_i = k_i^{\theta}$, where θ is a tunable parameter. Previous studies have shown that the preferential allocation strategy $\Delta L_{ij} = L_i \frac{L_j}{\sum_{n \in \Gamma_i} L_n}$ is closer to the actual situation, and the larger the initial load, the larger the redistribution load. Γ_i is the set of normal nodes around the failure node i. Fig. 1 shows the relationship between load and capacity. The larger the initial load, the smaller the ratio of redundant capacity. This is an objective phenomenon, and the capacity can be written as follows: $C = L + \Delta C$, where the value of L refers to the basic capacity requirements and is fixed. The value of ΔC refers to the redundant capacity, which is variable and determines the additional cost. The node that has a large initial load requires much more basic capacity, and the larger the basic capacity, the greater the cost under the same value of redundant capacity ΔC. Therefore, limited by the cost, the larger the initial load, the smaller the ratio of redundant capacity. Compared to the features of the preferential allocation strategy, the properties of the load–capacity model are completely contrary. Because of this contradiction, cascading failure can cause huge losses.

2.2. Repair model

At present, most of the cascading impact is applied in cascading failure, which is caused by deliberate attack. Few studies have investigated the phenomenon of secondary failure caused by improper repair. Most research on network restoration are confined to the static model, which does not apply to all situations. In other words, sometimes it can repair the damaged network but cannot achieve the goal, which is related to the timeliness. Therefore, this is not an efficient repair model. The circumstance of dynamic repair model is harsh and changeable, and different repair strategies have completely different repair characteristics. Maintenance personnel are involved in the repair process of a damaged network, and therefore, determine whether energy transfer allowed between nodes is controllable. According to this feature, we divided the influence of the cascade effect into 3 circumstances, encompassing all the possibilities of energy transfer based on local dependence: