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An approach for modeling vulnerability of the network of networks

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HIGHLIGHTS

- A framework is given to study the vulnerability of the network of networks.
- The interdependency between networks is introduced in detail.
- An interdependent urban electrified rail network is investigated in this paper.
- The functionality loss of the rail network subjected to power failures possesses a smallest value.
- The larger the dependent intensities are, the higher the vulnerability of the system is.

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ABSTRACT

In this paper, a framework is given to model the network of networks and to investigate the vulnerability of the network of networks subjected to failures. Because there are several redundant systems in infrastructure systems, the dependent intensity between two networks is introduced and adopted to discuss the vulnerability of the interdependent infrastructure networks subjected to failures. Shanghai electrified rail transit network is used to illustrate the feasibility and effectiveness of the proposed framework. Because the rail network is dependent on the power grid and communication network, the corresponding power grid and communication network are also included in this system. Meanwhile the failures to the power grid and communication network are utilized to investigate the vulnerability of the rail network. The results show that the rail network strongly depends on the power grid and weakly depends on the communication network, and the transport functionality loss of the rail network increases with the increase of dependent intensity. Meanwhile the highest betweenness node-based attack to the power grid and the largest degree node-based attack to the communication network can result in the most functionality losses to the rail network. Moreover, the functionality loss of the rail network has the smallest value when the tolerance parameter of the power grid equals 0.75 and the critical nodes of the power grid and communication network can be obtained by simulations.

1. Introduction

Infrastructure networks have become the lifeline and backbone of the modern society, such as power grid networks [1–5], transportation networks [6–9], pipeline networks [10], communication networks [11] and internet [12,13]. Since the infrastructure networks play crucial roles in the development of the society, the securities of the critical infrastructures

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must be paid much attention in the future. The failures of critical infrastructure networks have been investigated from many aspects and the researchers have obtained many valuable results [14–17]. Based on the importance of critical infrastructures, many researchers have devoted to this research field in the past ten years.

It is obvious that most of the infrastructure networks are not self-sufficient; there are several relationships between different critical infrastructure networks [18–21], and these correlations play important roles in the modern society. Recently, interdependent infrastructure networks have been given a lot of concern, and the researchers investigated them from many aspects [22–26]. Meanwhile, we know that the interdependent infrastructure networks are very fragile to the failures [22,23], and Ouyang et al. [24] gave a methodological approach to analyze the vulnerability of interdependent infrastructures. Johansson and Hassel [27] gave an approach for modeling interdependent infrastructures and investigated the vulnerability of the interdependent networks. Meanwhile a railway network was given as an example to illustrate the effectiveness of the approach [27]. Gao et al. investigated the robustness of a network of networks [28]; Ouyang and Duenas-Osorio gave an approach to design interface topologies across interdependent urban infrastructure systems [29]. Wang et al. investigated the vulnerability of interdependent infrastructure systems under edge attack strategies [30] and gave a methodological framework to study the vulnerability of interdependent infrastructure systems [31]. Holden et al. [32] gave a network flow model for interdependent infrastructures at the local scale. Moreover, the defense and attack of complex and dependent systems were investigated by Hausken [33] and the uncertainty of interdependent critical infrastructures subjected to extreme events is considered as a very important aspect to assess the reliability and robustness of the systems. Barker and Haimes [34] assessed the uncertainty of interdependent infrastructures subjected to extreme events. Furthermore, Bobbio et al. [35] studied the unavailability of critical SCADA communication.

Additionally, there are many interdependent and dependent relationships among critical infrastructure networks, for example, the electrified railway network depends on the power grid; the pipeline network also depends on the power grid; the transportation network depends on communication networks; the communication network also depends on power grids, etc. In short, the interdependent infrastructure networks play more and more important roles in the modern society. In this paper, the interdependency is divided into strong interdependency and weak interdependency; meanwhile the dependency is also divided into strong dependency and weak dependency; therefore the dependent intensity is included in this paper to investigate the vulnerability of the interdependent infrastructure networks.

The paper is organized as follows. Section 2 introduces the dependency and interdependency between critical infrastructure networks, and the visualizations are given to illustrate their interactions. Section 3 gives the model of interdependency based on the electrified rail network and presents an example of the urban railway transit network. The failures of interdependent networks are investigated to assess the vulnerability of the system and to illustrate the effectiveness of the methodology in Section 4. Finally, conclusion is given in Section 5.

2. Dependency and interdependency

In this section, the dependency and interdependency of the network of networks are illustrated by the virtual graphics. The dependency between two networks includes the strong dependency and weak dependency; strong dependency presents that one critical infrastructure network strongly depends on another network, that is to say, the failures to one network can result in large damages to another network. If two networks are strongly dependent on each other, it illustrates that they have the strong–strong interdependency with each other. If the network π_1 strongly depends on the network π_2 and the network π_2 weakly depends on the network π_1, it is called strong–weak interdependency. Simultaneously, the weak–weak interdependency can be also defined if two networks weakly depend on each other. Same as the interdependency, the unilateral dependency between two networks also contains strong dependency and weak dependency, and the unilateral dependency is the most common case in the world. In the modern society, most of the dependencies between two networks are the strong dependencies.

Fig. 1 gives the visualizations of dependency and interdependency between two networks. The same structures of the two networks are given in Fig. 1, and the same structures do not affect the research of the dependency and interdependency between the two networks. If the two networks have different topological structures, the interdependent regulations are different from the patterns shown in Fig. 1. The starting points of the arrows belong to the master networks and the end points of the arrows are included in the slave networks, so the power grid is the master network and the railway network belongs to the slave network for the electrified railway system. Fig. 2 describes the dependency and interdependency among three networks, and these three networks, upper network, middle network and lower network, represent different critical infrastructure networks. From the graph *d* in Fig. 2, we know that the upper network is the master network, the middle network is the slave network of the upper network and it is the master network of the lower network, and the lower network is the purely slave network. The graph *e* of Fig. 2 shows that the upper network and the middle network are the interdependent networks, they are the master and slave networks for each other, and same as the graph *d* of Fig. 2, the lower network is also the slave network of the middle network. According to the graph *f* of Fig. 2, it is known that the upper network is the master network of the middle network and the lower network, and the middle network is also the master network of the lower network. The interdependency among multiple networks has serious impacts on the social security, and it makes the infrastructure networks become more and more fragile.

From the above analyses, we know that the dependency can be divided into strong dependency and weak dependency between networks; therefore we give a parameter called dependent intensity to assess the strong and weak dependencies,