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The Research On Statistical Identification of Critical Infrastructure Chain Failure Paths

Jingwen Zhang[1], Lili Rong[1],Chunbing Bao[2,*]

[1]School of Economics and Management, Dalian University of Technology, 2 Lingong Road, Ganjingzi District, Dalian and 116024, China
[2]School of Management, Shandong University, 27 Shandanan Road, Licheng District, Jinan and 250100,China

Abstract

Using literature studies, case studies, empirical induction and statistical identification, we proposed an analytical framework based on empirical induction to identify and analyze chain failure problems among interdependent critical infrastructures. A case database of critical infrastructure chain failures was established, and as the research emphasis the identification method of critical infrastructure chain failure paths was constructed and designed. The chain failure paths of the critical infrastructure and its sub-networks in China and other countries and regions were discussed. Logical relationships of critical infrastructure chain failures were extracted from the established database covering 229 critical infrastructure chain failure cases. Statistics, identification, and analysis of data were conducted to form a quantitative assessment and understanding of the vulnerability of interdependent critical infrastructure networks. Finally, identification methods and probabilistic statistical methods for chain failure paths of critical infrastructure were designed and applied to the case base of this paper. Using this approach, fatal and severe failure paths of critical infrastructure can be identified and the efficiency of the relevant authorities' inspection work will be improved under cost constraints.

Keywords: Critical infrastructure， Interdependence， Chain failure， Statistical identification

1. Introduction

The critical infrastructures are the basic engineering facilities which guarantee the normal operation of city “life” and maintain the modern urban and regional economic function. They are found throughout critical systems, such as water supply and water treatment, electricity, communications, transportation, natural gas and oil, government services, banking and commerce, emergency services systems, etc. Due to the interdependent relationship between critical infrastructures, when one critical infrastructure is destroyed, it may trigger the failure of other critical infrastructures, even in a sequential chain development, paralyzing the entire city. This

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makes it particularly important to study networks of critical infrastructure systems with interdependent relationships.

In the research on the classification of infrastructure interdependence, five perspectives are mainly involved: input-output [1], event-attribute [2] structure-function [3] service provision [4], network flow [5]. At present, the input-output perspective is widely adopted by scholars, which is also adopted in this paper.

For qualitative and quantitative research on the interdependence of critical infrastructure, there are two mainstream research frameworks for qualitative research at present, one of which is the six-dimension framework proposed by Argonne National Laboratory [1], and the other is the CIMS framework proposed by Iowa National Laboratory [6].Quantitative research is divided into experience-based and knowledge-based approaches and modeling and simulation. The models involved in modeling and simulation mainly include network diagram model [4,7], agent simulation model [8], system dynamics model [9], economic model [10], etc. Although the modeling framework and tools are different, there are two main modeling ideas in general: integrated model analysis and coupled analysis [11]. The so-called integrated model analysis means that the analysis attempts to place several critical infrastructures and their interdependencies within a framework. Coupling analysis refers to the coupling of multiple single critical infrastructure models together for simulation analysis with respect to multiple infrastructure subsystems. Most of the research on infrastructure interdependence has been based on modeling and simulation analysis, which is based on a single incident or case[12], and on analyzing and understanding infrastructure interdependence through the hypothesis-led paradigm. Correspondingly, empirical analysis is rarely used, which may be related to the difficulty in obtaining data. And this paper is trying to use a method to establish a statistical identification framework of critical infrastructure chain failure path, deepen the study of critical infrastructure chain failure path and the understanding of the vulnerability of modern urban operation.

2. Framework for critical infrastructure chain failure path analysis

2.1. Definition of critical infrastructure

The US Department of Land and Resources took the lead in promulgation of the national infrastructure protection plan (NIPP)[13]. In 1997, In the report of the U.S. President's Commission on the Protection of Critical Infrastructure Protection (PCCIP), they define critical infrastructure as follows [14]: CI refers to those facilities whose failure or damage will weaken national defense and have a significant impact on economic security. Eight critical infrastructure items are well defined in the report: power systems, transportation systems, water and sewer systems, communications systems, oil and gas, banking and commerce, government services, and emergency services. It is also the classification standard adopted in this paper.

2.2 Critical infrastructure chain failure and failure order

Critical infrastructure often fails due to interdependence. It can be divided into three main forms: one is "cascading failure", which means that when a certain infrastructure is disturbed, then it cause the component failure of the second infrastructure, resulting in the second infrastructure to be disturbed; The second is "escalation failure", when one infrastructure suffers from disturbance, it will aggravate the degree of disturbance suffered by another infrastructure or prolong its recovery time. The third is "common cause failure", which refers to the disturbance of two or more infrastructure networks due to common causes at the same time. These three forms of infrastructure failure are different in causality, but they all lead to serious consequences affecting the operation of the city [1].

In 2001, James P.Peerenboom, director of the Center for Infrastructure Protection at Argonne National Laboratory in the United States, used a six-dimensional framework to classify the cascading effects of infrastructure failures in the IEEE Journal of Control Systems. It can be divided into first-order effect, second-order effect, third-order effect, etc [1]. For example, in the state of power failure, the resulting failure of the transport pipeline in the oil pipeline can be regarded as the first-order effect, the resulting failure of the storage terminal caused by the shortage of gasoline and diesel can be regarded as the second-order effect, and the obstruction affecting the train transport plan can be regarded as the third-order effect, and so on. For another example, in the state of power failure, the water shortage resulting in the interruption of irrigation service can be regarded as the first-order effect, the crop failure caused by the power failure can be regarded as the second-order effect, and the impact of financial damage on the financial system can be regarded as the third-order effect, and so on.

2.3. Construction of critical infrastructure chain failure case database

The core of this study is to establish a case database containing information about the chain failure of critical infrastructure. The data involved in the case were all reported by public media channels, such as newspapers, magazines and other related publications, as well as online media. Currently, 229 major critical infrastructure failure events in recent years have been collected in this case database. The failure event covers the entire life cycle of critical infrastructure risk management, including the construction, operation, maintenance and equipment aging phases. Failure events involve natural disasters, accidents, public health and social security. Failure events database include 156 cases in China and 73 cases in countries and regions out of China.(including Japan, the United States, Indonesia, Malaysia, the Philippines, Brazil, India, Mexico, etc.).

Logical relationship statistics of critical infrastructure chain failures are extracted from the case overview. The causal chain in the process of critical infrastructure chain failures is indicated by arrows pointing to (→). A structured description of critical infrastructure chain failures in a typical failure scenario is extracted as follows.

Rainstorm→
- Damage of water conservancy facilities→Damage of power facility→ Telecommunication interruption
- Damage of airport, Bridges and other transportation facilities→Obstructed rescue

Using social network analysis and survey statistical software such as UCINET to analyze and process the data, the occurrence of chain failures of critical infrastructures are drawn, as shown in Figure 1 below:

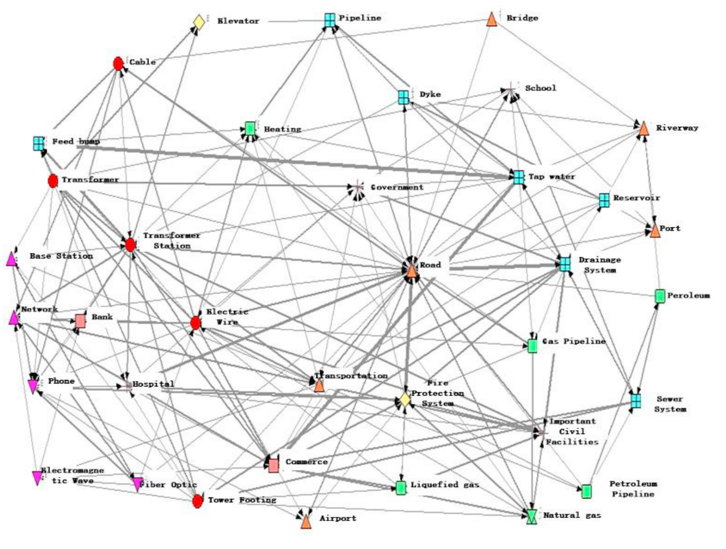

Fig. 1. Critical infrastructures chain failure response figure - according to the specific infrastructure statistics.

2.4. Methods for identifying critical infrastructure failure paths

In this paper, the collected case base is summarized into various chain failure chains, which are classified and merged, and the divided according to the ascending sequence of statistical chain failure times. This paper divides the failure states into slight failure, medium failure, severe failure and fatal failure. The path with less than α one failure is identified as a slight chain failure path. If the number of failure is greater than or equal to α and less than β , it is identified as medium chain failure path. If the number of failures is greater than or equal to β, and less than γ , it is identified as a severe chain failure path. If the number of failures is greater than or equal toγ , it is identified as a fatal failure path. Specific identification methods are as follows:

Propagation path of critical infrastructure chain failure:

$$X_1 \overset{a}{\rightarrow} X_2 \ldots \overset{b}{\rightarrow} X_n \tag{1}$$

Where, $X_1, X_2 \ldots X_n$ represents a type of infrastructure, a is the number of times of primary and secondary failure between X_1 *and* X_2 - any two types of infrastructures, b is the number of times of the last failure by the path from X_2 to X_n.

$$\begin{gathered}
\mathrm{a} < \alpha, \mathrm{b} < \alpha \Longrightarrow Slight\ Failure \\
\alpha \le \mathrm{a} < \beta \begin{cases} b < \alpha \Rightarrow Slight\ Failure \\ \alpha \le b < \beta \Rightarrow Mediium\ Failure \end{cases} \\
\beta \le \mathrm{a} < \gamma \begin{cases} b < \alpha \Rightarrow Slight\ Failure \\ \alpha \le b < \beta \Rightarrow Mediium\ Failure \\ b < \alpha \Rightarrow Sevre\ Failure \end{cases} \\
\alpha \ge \gamma \begin{cases} b < \alpha \Rightarrow Slight\ Failure \\ \alpha \le b < \beta \Rightarrow Mediium\ Failure \\ \beta \le b < \gamma \Rightarrow Mediium\ Failure \\ b \ge \alpha \Rightarrow \text{Fatal Failure} \end{cases}
\end{gathered} \tag{2}$$

Where, 0<α<β<γ, according to the statistics of a path with the highest number of failures determine the value of γ, and then take the Four-level classification standard to determine the numerical values of α and β. In this paper, different situations in China and out of China are identified statistically

2.5. Probabilistic statistical methods for critical infrastructure failure paths

One of the implications of this study is to predict future chain events in critical infrastructure, thus providing reference and assistance to relevant departments in making emergency decisions. First of all, according to the statistical induction of the chain failure of critical infrastructures in the case database, the failure probability of each type of critical infrastructure in primary, secondary and tertiary failures can be calculated, as shown in Table 1. Probabilistic products are then performed for specific critical infrastructures where failure paths are identified and probabilistic statistics are performed. In this paper, the probability statistics are carried out only for the severe chain failure paths and fatal chain failure paths, and the occurrence probability of the obtained paths is sorted out as the prediction result.

Table 1. Three-level probability statistics of failed nodes.

Critical Infrastructure	Facilities / Failure Level	Primary	Secondary	Tertiary
A syestem	X_1	P_{11}	P_{12}	P_{13}
	X_2	P_{21}	P_{22}	P_{23}

B system	X_3	P_{31}	P_{32}	P_{33}
	X_4	P_{41}	P_{42}	P_{43}
…	…	…	…	…
X system	X_n	P_{n1}	P_{n2}	P_{n3}

Then, for the failure path: $X_i \to X_j \to X_k, i, j, k \in (1, n)$, the failure probability:

$$P(X_i \to X_j \to X_k) = P_{i1}P_{j2}P_{k3} \tag{3}$$

3. Path identification and probability statistics of chain failures of critical infrastructures

3.1 Failure path identification of critical infrastructure sub-networks in China

According to statistics Drainage system → Road → Fire protection system is the path has the highest number of failures of 12, thus a unified identification scheme can be determined. Assign γ a value of 12 in the identification scheme, and then by the four-level division standard,$\alpha = 4, \beta = 8$.

$$\begin{aligned}
&\mathrm{a} < 4, \mathrm{b} < 4 \Rightarrow Slight\ Failure\\
&4 \le \mathrm{a} < 8 \begin{cases} b < 4 \Rightarrow Slight\ Failure \\ 4 \le b < 8 \Rightarrow Mediium\ Failure \end{cases}\\
&8 \le \mathrm{a} < 12 \begin{cases} b < 4 \Rightarrow Slight\ Failure \\ 4 \le b < 8 \Rightarrow Mediium\ Failure \\ 8 \le b < 12 \Rightarrow Severe\ Failure \end{cases}\\
&\alpha \ge 12 \begin{cases} b < 4 \Rightarrow Slight\ Failure \\ 4 \le b < 8 \Rightarrow Mediium\ Failure \\ 8 \le b < 12 \Rightarrow Mediium\ Failure \\ b \ge 12 \Rightarrow \text{Fatal Failure} \end{cases}
\end{aligned} \tag{4}$$

Table 2. Paths identification of critical infrastructure sub-network chain failure in China.

Failure path state	Path description
Slight Failure	Commerce → Fire protection system → Road → Hospital
	Electric wire → Feed pump…
Medium Failure	Transformer station → Network → Bank
	Transformer station → Road → School ...
Severe Failure	Drainage system → Road → Hospital
	Drainage system → Transportation → Fire protection system
Fatal Failure	Drainage system → Road → Fire protection system

As shown in Table 2, drainage system is the main source of failure of critical infrastructure sub-network in China, road and transportation are the two most easily spread critical infrastructure, in general, fire protection system is the most affected.

3.2. Failure path identification of critical infrastructure sub-networks in countries and regions other than China

According to statistics Drainage system → Road → Fire protection system is the path has the highest number of failures of 6, thus a unified identification scheme can be determined. Assign γ a value of 6 in the identification scheme, and then by the four-level division standard,$\alpha = 2, \beta = 4$.

$$\begin{aligned}
&\mathrm{a} < 2, \mathrm{b} < 2 \Rightarrow Slight\ Failure\\
&2 \le \mathrm{a} < 4 \begin{cases} b < 2 \Rightarrow Slight\ Failure \\ 2 \le b < 4 \Rightarrow Mediium\ Failure \end{cases}
\end{aligned}$$

$$4 \leq \text{a} < 6 \begin{cases} b < 2 \Rightarrow Slight\ Failure \\ 2 \leq b < 4 \Rightarrow Mediium\ Failure \\ 4 \leq b < 6 \Rightarrow Sevre\ Failure \end{cases} \tag{5}$$

$$\alpha \geq 6 \begin{cases} b < 2 \Rightarrow Slight\ Failure \\ 2 \leq b < 4 \Rightarrow Mediium\ Failure \\ 4 \leq b < 6 \Rightarrow Mediium\ Failure \\ b \geq 6 \Rightarrow \text{Fatal Failure} \end{cases}$$

Table 3. Paths identification of critical infrastructure sub-network chain failure other than China.

Failure path state	Path description
Slight Failure	Drainage system → Tower footing
	Cable → Electromagnetic wave → Commerce…
Medium Failure	Road → Cable → Feed pump
	Water pipe → Tap water → Heating ...
Severe Failure	Road → Fire protection system → Hospital
	Drainage system → Transportation → Fire protection system
Fatal Failure	Drainage system → Road → Fire protection system

As shown in Table 3, drainage system is the main source of failure of critical infrastructure sub-network out of China, in general, fire protection system is the most affected.

3.3. Probability statistics of critical infrastructure failure paths in China

Table 4. The probability statistics of critical infrastructure network chain failure paths in China.

Failure path state		Primary	Secondary	Tertiary	Probability
Severe Failure	Water system → Electric system → Emergency management system	0.2664	0.1977	0.1708	0.0091
	Electric system → Water system → Government service system	0.2548	0.1567	0.1329	0.0053
Fatal Failure	Transportation system → Electric system → Water system	0.2393	0.1977	0.1898	0.0089
	Water system → Transportation system → Emergency management system	0.2664	0.22387	0.1708	0.0101
	Electric system → Transportation system → Water system	0.25482	0.2238	0.1898	0.0108

The probability statistics of severe failure paths and fatal failure paths among the failure paths of critical infrastructure in China are arranged in descending order of probability:

Electric system → Transportation system → Water system;
Water system → Transportation system → Emergency management system;
Water system → Electric system → Emergency management system;
Transportation system → Electric system → Water system;
Electric system → Water system → Government service system.

3.4. Probability statistics of critical infrastructure failure paths other than China

Table 5. The probability statistics of critical infrastructure network chain failure paths other than China.

Failure path state	Primary	Secondary	Tertiary	Probability

Severe Failure	Water system → Transportation system → Emergency management system	0.2841	0.3068	0.1579	0.0138
	Water system → Transportation system → Telecommunication System	00.2841	0.3068	0.1579	0.0138
Fatal Failure	Water system → Transportation system → Government service syste	0.2841	0.3068	0.2456	0.0214

The probability statistics of severe failure paths and fatal failure paths among the failure paths of critical infrastructure out of China are arranged in descending order of probability:
Water system → Transportation system → Government service system;
Water system → Transportation system → Telecommunication System;
Water system → Transportation system → Emergency management system.

3.5. Probability statistics of failure paths of critical infrastructure sub-networks in China

Table 6. The probability statistics of critical infrastructure sub-network chain failure paths in China .

Failure path state		Primary	Secondary	Tertiary	Probability
Severe Failure	Drainage system → Road → Hospital	0.1698	0.1305	0.0822	0.0018
	Drainage system → Transportation → Fire protection system	0.1698	0.0671	0.1265	0.0014
Fatal Failure	Drainage system → Road → Fire protection system	0.1698	0.1305	0.1265	0.0028

The probability statistics of severe failure paths and fatal failure paths among the failure paths of critical infrastructure sub-networks in China are arranged in descending order:
Drainage system → Road → Fire protection system;
Drainage system → Road → Hospital ;
Drainage system → Transportation → Fire protection system.

3.6. Probability statistics of failure paths of critical infrastructure sub-networks other than China

Table 7. The probability statistics of critical infrastructure sub-network chain failure paths other than China .

Failure path state		Primary	Secondary	Tertiary	Probability
Severe Failure	Road → Fire protection system → Hospital	0.1704	0.1363	0.1052	0.0024
	Drainage system → Transportation → Fire protection system	0.1363	0.1136	0.1403	0.0021
Fatal Failure	Drainage system → Road → Fire protection system	0.1363	0.1477	0.1403	0.0028

The probability statistics of severe failure paths and fatal failure paths among the failure paths of critical infrastructure sub-networks in China are arranged in descending order:
Drainage system → Road → Fire protection system;
Road → Fire protection system → Hospital;

Drainage system → Transportation → Fire protection system.

4. Conclusion

In this paper, the critical infrastructure and its sub-networks in China and other countries and regions are analyzed through the design of the critical infrastructure chain failure path identification method and probability statistical method. The study found that most of the severe and fatal failure paths identified were caused by water supply and water treatment systems and power systems, which were most likely to affect the transportation system, and then lead to the failure of government services and emergency services. According to the statistics of critical infrastructure failure paths in China, two fatal failure paths and three severe failure paths were identified. According to the statistics of failure paths of critical infrastructure in countries and regions other than China, one fatal failure path and two severe failure paths were identified. According to the statistics of the failure paths of China's critical infrastructure sub-networks, one fatal failure path and two severe failure paths are identified. According to the statistics of failure paths of critical infrastructure sub-networks in countries and regions other than China, one fatal failure path and two severe failure paths were identified.

Therefore, relevant departments can strengthen prevention and monitoring of possible chain failure events more carefully and specifically based on the identified paths of fatal failure and severe failure, which can shorten the investigation time to a certain extent and thus improve the work efficiency of the department. The research method in this paper can help decision-makers quickly find the failure path with a high probability of occurring in this region, and truly strengthen the protection efforts to prevent the occurrence and development of crisis events.

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