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A method for exploring the interdependencies and importance of critical infrastructures

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ABSTRACT

The failure of critical infrastructures may be hazardous to the general population, the economy, even national security. Disruptions in one type of infrastructure often transverse to other dependent infrastructures and possibly even back to the infrastructure where the failure originated. Unlike previous studies, this paper proposes a new method which addresses this interdependency and the feedback effects between different types of critical infrastructures by using a hybrid model which is a combination of both the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and the Analytic Network Process (ANP) (called DANP). The proposed model not only remedies the shortcomings in the original ANP method but is also more reasonable. Data related to infrastructure in Taiwan are used to demonstrate this method. The new method can effectively capture the interdependency and prioritizes the critical types of infrastructure.

1. Introduction

Critical infrastructures are physical and logical systems with major importance for public welfare [1]. They can be technological networks, such as energy supply, water supply, oil and gas supply and transport networks, or banking and government, health care systems, and information and communication technology (ICT) systems [2,3]. If the vulnerabilities in infrastructures are exploited, they could be disrupted or disabled, possibly causing severe consequences such as a loss of life, economic losses, and even damages to national security [4]. Critical infrastructures interact at different levels, and a failure in one type of infrastructure may impact the functionality of others. It is thus becoming increasingly important to take these interdependencies into account when assessing the vulnerability of technical infrastructure. The significant societal importance of these types of infrastructure and their interrelatedness means that sufficient safety and security measures need to be identified in order to reduce the risks of failure [5].

Many efforts are currently being devoted to develop models and methods capable of analyzing interdependent infrastructure systems. Johansson and Jonsson [6] divided those methods into two categories – the empirical approaches and the predictive approaches. Empirical approaches aim at studying past events in order to increase our understanding of infrastructure dependencies. Often, the purpose is to find patterns that may be interesting with respect to political decisions. For instance, these can be patterns related to the consequences for a society, or how often failures propagate between the various infrastructures. Examples of empirical approaches are those of the University of British Columbia [7,8], Zimmerman and Restrepo [9] and Restrepo et al. [10]. Predictive approaches mainly focus on modeling and/or simulating the behavior of a set of interconnected infrastructures, for example, to assess how disturbances cascade through the systems. A wide range of different perspectives and methods of representing the systems of interest exist, including economic-mathematical models [11], economic-system dynamic models [12], agent-based models [13], and network modeling approaches [14]. The challenges for understanding, characterizing and modeling these systems are immense, and the current efforts in this field are still in an early stage [15]. Yusta et al. [16] made a good summarization that illustrated more than 50 methods with different methodologies, applications and software tools for critical infrastructure protection. The existing methods or models address the same issue, the impact of interdependencies, but from different viewpoints. Therefore, we can conclude that there is no universal, all-encompassing model.

Differing from prior studies, here we apply a model which uses the graph-theory based Decision Making Trial and Evaluation Laboratory (DEMATAL) method combined with the Analytic Network Process (ANP) approach (called DEMATEL-based ANP, or DANP) to construct the interdependent relationships between infrastructures [17,18]. The DEMATEL method is a potent method that uses the knowledge of experienced experts to layout the structural model of a system. It confirms the relationship between various perspectives, enhancing our understanding of the complex issues related to the critical infrastructures. An influential network-relationship map (INRM) maps

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out the complex relationships among infrastructure systems, which, combined with the DANP can help to measure the mutual importance of each critical type of infrastructure. The application of the proposed method to a discussion of critical infrastructure is an innovative idea. The parts of critical infrastructures in Taiwan are modeled as four systems with interdependencies between these systems. It is shown how the model can be employed. The infrastructure that contributes most to cascading failure is identified through this analysis. This paper contributes to the existing literature by presenting a soft computing method instead of a computer simulation with that required the collection of a large amount of data to assess the interdependency and importance of critical infrastructures.

2. Critical infrastructure interdependency

Several frameworks and methods for characterizing and analyzing interdependency for critical infrastructures have been suggested. One of the most cited frameworks for characterization is the one proposed by Rinaldi et al. [3]. They identified four types of critical infrastructure interdependency – physical, cyber, geographic and logical. Physical interdependency is related to material flows between infrastructures. As an example, a gas- or coal-fired power plant relies on transportation systems to ship in raw materials while the transportation system itself requires a continuous supply of electricity for uninterrupted operation of traffic signals and lights. Cyber interdependency refers to the state of a system that is dependent on information transmitted through an information infrastructure. Geographic interdependency is formed as a result of physical proximity, such as electrical cables that run along a bridge. Logical interdependency includes all other types of interdependencies, for example, a cost-cutting drive that reduces the frequency of water quality monitoring at a water treatment plant, thereby increasing the chances of drinking water contamination [19]. Zimmerman and Restrepo [9] proposed a somewhat coarser classification where infrastructure interdependencies are either seen as functional or spatial/geographic.

In critical infrastructure protection, interdependency within a critical infrastructure is of major concern to government. In response, an increasing amount of studies are being conducted to understand the nature of critical infrastructure interdependency. Yusta et al. [16] provided a summary of the state-of-the-art energy security relating to critical infrastructure protection. They pointed out two important trends in methodologies and modeling. The first trend is related to the identification of methods, techniques, tools and diagrams to describe the current state of infrastructure. The other trend focuses on the dynamic behavior of infrastructure system by means of simulation techniques. Apostolakis and Lemon [14] applied multi-attribute utility theory to screen, identify, and prioritize the physical points of vulnerability for three types of infrastructure (i.e., electrical power, water and natural gas). Setola et al. [20] applied an input–output model for analyzing the cascading effects induced by critical infrastructure dependencies and interdependencies. Their analysis was mainly based on the technical and operational data collected by interviewing experts. Robert [21] developed a method to define and assess the propagation of vulnerability, or cascading effect, of interrelated subsystems within hydroelectric networks. Houck et al. [22] investigated the interdependency with the telecommunications system by conducting simulations of telecommunication failures at various stages of the disaster. Chai et al. [19] applied social network theory to prioritize oil and gas industry protection in a networked critical infrastructure system. They identified oil & gas, information & communication technologies and electricity as three types of infrastructure that are most relied upon by other types. Hellstrom [23] presented an analytical planning framework for hypothesizing, formulating and mitigating vulnerability in critical infrastructures. He used cyber attacks on vital public functions as an example and proposed some key principles for systemic vulnerability in critical types of infrastructure across different sectors of society.

Besides identifying infrastructure vulnerability as a contributing result of infrastructure interdependency, efforts are also being made to prioritize the importance of critical infrastructure protection. Zimmerman [24] identified water mains as the key infrastructure whose failure most often leads to the disruption of other infrastructures. His analysis is based on a database compiled from accidents occurring during construction, maintenance, or operation of these infrastructures. Biersack et al. [25] ranked the importance of some of the major critical infrastructures by expert opinions. Other methods, such as social network theory [19], an input–output inoperability model [21], dynamic simulation [26,27] or knowledge management [28] also need some degree of expert inputs. The advantage of expert opinions lies with the intimate knowledge they have gained over a long period of time in their area of expertise. One inherent problem with expert judgment is that their opinions may be biased toward personal experience and concerns [19].

Johansson and Jonsson [6] distinguished between direct (first order) or indirect (second order; inter) dependencies. If, for example infrastructure i depends on infrastructure j (j influences i), and infrastructure j depends on infrastructure k (k influences j), there is a second order (indirect) dependency between i and k (k influences i indirectly). Such higher order dependencies are much more difficult to spot, and it is more difficult to make sense of their effects without explicit modeling and simulation [29]. Based on the above review, our first goal is to explore the complex and higher order dependent network systems in the critical infrastructures. The second goal is to investigate the importance of critical infrastructure and provide some management implications.

3. Proposed method

This section introduces the proposed method (DANP) for not only constructing the interdependent structure but also obtaining the influential weights of criteria (critical infrastructures).

3.1. DANP method

The DANP is a method that combines the original DEMATEL and ANP methods. The method can be summarized as follows [30–32]:

Step 1: Calculate the direct relation average matrix

Assuming that the scales 0, 1, 2, 3 and 4 represent the range from "no influence" to "very high influence", respondents are asked to propose the degree of direct influence each criterion (sub-sector) i exerts on each criterion j, which is denoted by d_{ij}, using the assumed scales. It is worth noting that a 0–4 scale is applied in our survey instead of 0–9 as in the original ANP analysis. The reason is that our ANP analysis is based on the DEMATEL method where a 0–4 scale is usually utilized. Furthermore, our prior surveys also indicate that with the 0–4 scale we can effectively distinguish the different degrees of influence for most respondents. A direct relation matrix is produced for each respondent, and an average matrix $\boldsymbol{D}$ is then derived from the mean of the same criteria in the various direct matrices for all respondents. The average matrix $\boldsymbol{D}$ is:

$$\boldsymbol{D} = \begin{bmatrix} d_{11} & \cdots & d_{1j} & \cdots & d_{1n} \\ \vdots & & \vdots & & \vdots \\ d_{i1} & \cdots & d_{ij} & \cdots & d_{in} \\ \vdots & & \vdots & & \vdots \\ d_{n1} & \cdots & d_{nj} & \cdots & d_{nn} \end{bmatrix} \tag{1}$$