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A rapid reliability estimation method for directed acyclic lifeline networks with statistically dependent components

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A B S T R A C T

Lifeline networks, such as transportation, water supply, sewers, telecommunications, and electrical and gas networks, are essential elements for the economic and societal functions of urban areas, but their components are highly susceptible to natural or man-made hazards. In this context, it is essential to provide effective pre-disaster hazard mitigation strategies and prompt post-disaster risk management efforts based on rapid system reliability assessment. This paper proposes a rapid reliability estimation method for node-pair connectivity analysis of lifeline networks especially when the network components are statistically correlated. Recursive procedures are proposed to compound all network nodes until they become a single super node representing the connectivity between the origin and destination nodes. The proposed method is applied to numerical network examples and benchmark interconnected power and water networks in Memphis, Shelby County. The connectivity analysis results show the proposed method's reasonable accuracy and remarkable efficiency as compared to the Monte Carlo simulations.

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1. Introduction

Lifeline networks, such as transportation, water supply, sewers, telecommunications, and electrical and gas networks, are fundamental to our environment, socio-economic development, and quality of life. Although composed of redundant components, they are still susceptible to natural hazards as evidenced by historical earthquake events such as the Loma Prieta earthquake in the USA in 1989, the Northridge earthquake in California in the USA in 1994, the Hyogo-ken Nanbu earthquake in Japan in 1995, and the Chile earthquake in 2010. To prevent the spread of disaster and to minimize the effects of natural and man-made hazards to these lifeline network systems, it is essential to provide prompt and effective pre-disaster hazard mitigation strategies and post-disaster recovery efforts based on rapid system reliability assessment.

System reliability assessment of lifeline networks is often carried out by a node-pair connectivity analysis which determines the reliable state of a network as the connectivity between the origin and destination nodes without considering the network flow quantities. This node-pair connectivity analysis has been used widely in the post-hazard reliability analysis of lifeline networks because it adequately and efficiently describes the impact of disasters on lifeline disruptions. The connectivity is a necessary condition of more sophisticated flow-based analyses, and it is important to study connectivity particularly for more complex lifeline systems. In spite of the simplicity of the node-pair connectivity analysis, this connectivity analysis is still challenging because lifeline networks are highly complex systems consisting of spatially distributed network components, intricate topology, uncertainties in actual conditions of network components and deterioration models, and interdependencies at the component and system levels [1]. Considering these complex natures, the reliability estimation of a node-pair connectivity problem is a difficult and complex task.

To overcome these challenges, many researchers have relied on Monte Carlo simulation (MCS) based methods because they are easy to implement. They just require the generation of random samples of hazard intensity measures and the corresponding uncertain status of network components with no need to identify complex connection system events [2]. However, the statistical nature of MCS based methods may need a large number of samples to achieve an acceptable level of convergence for very small or large probability estimation [3]. In addition, their computational efficiency depends on the number of nodes and links in a network as they use a path searching algorithm to check the connectivity between the origin and destination nodes for each sample [4]. Also, the random number generation process is computationally demanding especially when the components are statistically correlated as the process includes a matrix decomposition process such as the Cholesky decomposition. Depending on the nature of a given network, these challenges may hamper the rapid reliability estimation and prompt decision supports for post-disaster recovery efforts.

On the other hand, non-simulation based methods have been developed since the 1970s to calculate a node-pair connection probability by identifying the system events or sets without relying

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on random samples. They were developed based on Boolean algebra, set theory, Binary decision diagrams, network decomposition, recursive disjoint set identification, and minimal path identification [5–14]. They efficiently calculated the node-pair connection probability of general networks, and provided a high computational efficiency, even for large network problems, by providing bounds, approximation, or even exact solutions. However, all of the listed methods assume statistical independency between the states of network components and ignore the correlation of the states of network components, e.g., spatial correlations between water pipelines in a seismic disaster situation or the concurrent failure of water generation nodes due to the disconnection of a common power source, which need to be seriously considered in real lifeline network problems. Only a few attempts have been made to fully consider this network component dependency in the non-simulation based methods. Kang et al. [15] estimated the node-pair disconnection probability between each city and a critical facility in a bridge network based on the matrix-based system reliability (MSR) method and considered the correlated failures of bridges by identifying a common source random variable that represents the whole system correlation and makes the conditional independence between the states of components. In this approach, a special path searching algorithm was used to find all of the available paths between the origin and destination nodes. Lim and Song [2] recently proposed a network connectivity analysis method named the selective recursive decomposition algorithm by improving the recursive decomposition algorithm (RDA) developed by Li and He [11]. The selective RDA was applied to lifeline network problems, such as gas and water transmission networks under seismic hazards, and provided quickly converging probability bounds compared to the original RDA by identifying the most reliable disjoint link and cut sets between the origin and destination nodes. The correlations between the failures of the network components were considered in the calculation of each link or cut set by applying the efficient multivariate normal integration method developed by Genz [16]. Although the selective RDA improved the computational efficiency of the original RDA highly, it still needs to deal with the exponentially increasing number of link or cut sets to find the node-pair disconnection probability bounds. Lê and Walter [17] recently developed a probability bounds evaluation method for two-terminal network reliability when the components are statistically dependent. Their methods were applied to various numerical examples and provided reasonable probability bounds, but the tightness of the bounds was highly dependent on the number of components and the pattern of the component correlations.

In this paper, a very fast node-pair connection probability estimation method is proposed for reasonably large-sized networks, especially when the network components are statistically correlated. This method proposes a new recursive procedure for successively compounding the network components from the origin node to the destination node until one single super component representing the connectivity of the origin and destination nodes is obtained. This method uses the sequential compounding method (SCM) [18] to compound the network components, which offers computationally efficient compounding procedures and an extremely low error accumulation. The proposed method does not require an identification of a complex system event, e.g., a consideration of all of the path connection events, but it automatically considers the system event in the recursive compounding procedure while it fully considers the correlation between the network components. The performance of the proposed method is demonstrated by numerical network examples and a realistic benchmark lifeline network example aiming at a near-real-time reliability estimation of lifeline networks.

2. Proposed method

2.1. Network reliability analysis

In this paper, using the graph theory, a network is defined by a directed acyclic graph $G:=(N, L)$ where N and L denote nodes and links in a network, respectively. The network is restricted to an acyclic graph because the path search algorithm and the proposed recursive event identification steps can fall into loops during a path searching process. Nodes are labeled by numbers and links and their directions are represented by the two ordered node numbers at the two ends. In this paper, we use a node weighted modeling by assigning a failure probability to each node and by neglecting the failure probability of the links. Line type elements can be modeled by adding a node in their middle, representing the entire line element with the corresponding failure probability. The reliability of the network is defined by the probability of the connection between an origin node and a destination node, i.e., the probability that the origin node and the destination node are connected through at least one path.

The idea of the proposed method is to compound all of the network components (nodes) until they become a single component to represent the whole network node-pair connection. Fig. 1 illustrates this idea through a simple network example with five nodes. The nodes are indicated by circles, and the links are by directed arrows. In this example, we want to analyse the connectivity between the origin node, node 1, and the destination node, node 4. In step (a), node 5 obviously does not contribute to the connection between nodes 1 and 4; therefore, node 5 and its link from node 2 are removed in step (b). Then nodes 1 and 2 are compounded into super-node A, and nodes 1 and 3 are compounded into super-node B in steps (c) and (d), respectively. These two super-nodes are compounded to super-node C in step (e), and finally, super-node C and node 4 are compounded into super node D. Although this illustration shows the manual compounding procedure schematically, an automated procedure for successive network compounding will be proposed in this paper. In addition, when the failure events of the network components are correlated, compounding is successively performed for two of the components using the sequential compounding methods (SCM) developed by Kang and Song [18]. The details of the compounding procedure offered by SCM for the cases when two components are coupled by intersection and union are summarized in the next section.

2.2. A summary of sequential compounding method

Sequential compounding method (SCM) was developed by Kang and Song [18] to estimate the reliability of a given system composed of correlated components. In SCM, it is assumed that component failures

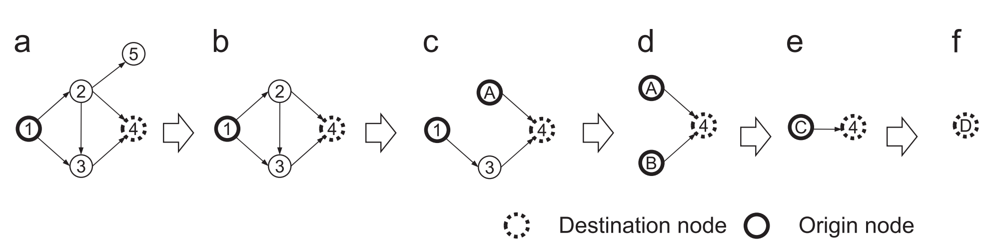

Fig. 1. An illustration of the proposed compounding procedure in a five-node network.

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