A Methodology for Identifying Critical Components in Physical Infrastructures

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Abstract

Climate change increases the risk of natural extreme events. These events can cause substantial loss of essential services such as electricity, water, and healthcare facilities. Assessing critical infrastructure vulnerabilities is an important planning task for decision makers to maintain supply of such services. Due to limitations of monetary budget in many decision making agencies, prioritization of critical infrastructures is required for planning emergency management investments. This paper proposes a methodology for identifying and prioritizing critical components in physical infrastructure. An infrastructure interdependency simulator, i2Sim, is used to account for interdependency links. A test case is used to illustrate the methodology.

Keywords: critical infrastructures, critical components, interdependencies

Résumé

Le changement climatique augmente le risque d'événements naturels extrêmes. Ces événements peuvent entraîner une perte substantielle des services essentiels tels que l'électricité, l'eau et les installations de soins de santé. L'évaluation des vulnérabilités des infrastructures essentielles est une tâche de planification important pour les décideurs de maintenir l'offre de ces services. En raison des limites de budget de monétaire dans de nombreux organismes de prise de décision, la hiérarchisation des infrastructures critiques est nécessaire pour les investissements de gestion des urgences de la planification. Ce document propose une méthodologie pour identifier et prioriser les composants critiques dans l'infrastructure physique. Un simulateur de l'interdépendance des infrastructures, i2Sim, est utilisée pour comptabiliser les liens d'interdépendance. Un cas de test est utilisé pour illustrer l'utilisation de la méthodologie.

Mots clés : infrastructures critiques, les composants critiques, l'interdépendance

1. Introduction

Over the last decades, disasters related to climate change have caused significant loss of lives and essential services. These losses can cause significant setbacks for economic and social development in the affected countries. According to the annual disaster statistical review, published by the Centre for Research on The Epidemiology of Disasters (CRED) in Belgium, 330 natural related disasters were reported in the world in 2013 only. In this year, more than 21,000 lives were lost and the economic losses were estimated to be US$ 118.6 billion [1].

Taking a wider look, it appears that the trend of economic losses during disasters is increasing over the last decades, as shown in Figure 1.

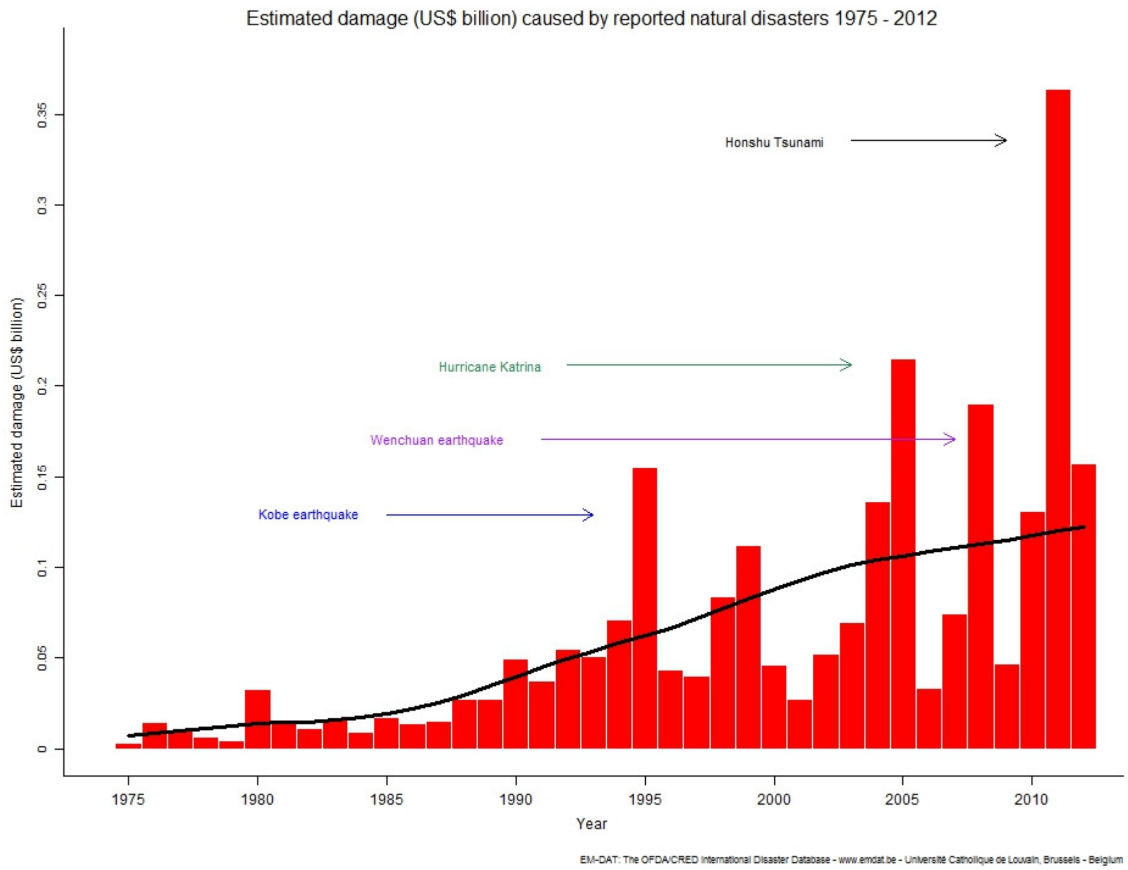


Figure 1. Estimated damage by reported natural disasters 1975-2012 – Courtesy The International Disaster Database (CRED)[2] .

Disaster preparedness is a huge challenge, but the consequences of being unprepared are devastating. Disaster preparedness is a preparation phase in the disaster management process. It includes all the activities that need to be implemented before a disaster strikes. A typical preparedness activity is infrastructure reinforcement, such as installing emergency power generators or building earthquake-resistant infrastructure. These activities require high investment costs. Therefore, disaster management agencies are faced with the challenge of planning their investment efficiently [3].

Prioritization methodologies can help in developing cost-effective investment plans for disaster management agencies. In this paper, a prioritization methodology is proposed for ranking critical components in multiple physical infrastructures, such as power networks, water networks, and healthcare facilities. The proposed methodology utilizes an infrastructure interdependencies simulator to assess failure scenarios. The physical infrastructure is modelled using a functional model that takes into consideration the interdependencies between different infrastructures. A single failure in one infrastructure, e.g. a water pump station, can cause huge degradation in the operations of multiple infrastructures due to cascading effects. The modelling approach used in this paper allows for capturing these interactions which improves the effectiveness of the prioritization methodology.

The rest of the paper is organized as follows: section 2 provides an overview of the relevant literature. Section 3 describes the modelling approach for simulating the physical infrastructures. Section 4 describes the proposed methodology for identifying and ranking the critical infrastructures. Section 5 uses a test model, based on real data, to show the applicability of the proposed methodology. Section 6 presents the conclusions and the directions for future work.

2. Related Work

In recent years, there has been an increased effort to protecting Critical Infrastructure (CI) from natural and man-made disasters. Every country defines CIs according to its national priorities. In Canada, Public Safety Canada refers to CIs as the “processes, systems, facilities, technologies, networks, assets and services essential to the health, safety, security or economic well-being of Canadians and the effective functioning of government. Critical infrastructure can be stand-alone or interconnected and interdependent within and across provinces, territories and national borders. Disruptions of critical infrastructure can result in catastrophic loss of life, adverse economic effects, and significant harm to public confidence.” [4]. As can be seen from the previous definition, CI’s definition is typically very broad. Thus, identifying and ranking methodologies are needed for developing CI protection plans.

Various research efforts focus on CI protection studies. There are different aspects in which these studies are conducted, such as modelling the CI [5,6], vulnerability assessment and failure analysis [7,8], and planning decision support systems [9]. The problem of identifying and ranking critical infrastructures has not yet gained enough attention and is often treated within the vulnerability and risk assessment studies. For example, a screening methodology based on Multi-Attribute Utility Theory (MAUT) and graph theory is proposed in [10] for ranking vulnerable building in the campus of the Massachusetts Institute of Technology. Another methodology is proposed in [11] for indentifying critical sets of components in large scale technical infrastructures. This methodology is based on measuring failure consequences in an electrical power network. Also, social network analysis is used in [12] to determine the priority of railway infrastructure assets. Most of the existing works uses topological models, represented as graphs, to measure the impact on the critical infrastructures and only a few consider a functional model, e.g. [11]. Those works that use functional models limit their analysis to one infrastructure without considering interdependent interactions with the other infrastructures.

3. Physical Infrastructure Modelling

Although research in modelling and simulating individual physical infrastructure is mature and rich, research in modelling and simulating multiple infrastructures is still a growing field. One of the main challenges in modelling multiple infrastructures is their growing complexity caused by their interconnectedness. Graph theory and social network analysis have been used in modelling multiple infrastructures by representing them as nodes connected with links. This approach exploits the topological interconnections among infrastructures but does not capture their functional behaviour, such as power network flow constraints or pressure constraints in water networks. Simulation-based analysis has emerged as powerful tool for studying multiple infrastructures. Depending on the simulation model, different characteristics can be captured, such as physical flows and event consequences. Due to the complexity of the modelled infrastructures, abstractions are required.

The methodology proposed in this paper uses a functional modelling approach that allows for capturing the interdependent interactions between multiple infrastructures. The methodology is based on measuring the failure consequences using an infrastructure interdependency simulator.

3.1 Infrastructure Interdependencies Simulator (i2Sim)

The infrastructure interdependencies simulator (i2Sim) is an event-driven, time-domain simulator for modelling and simulating multiple infrastructures [6]. i2Sim integrates dissimilar infrastructures by providing a common ontological framework built upon a cell-channel approach. The basic elements of the i2Sim ontology are defined as follows [6]:

Tokens: These are the resources needed or produced in the infrastructure, for example, electricity, water, and medicines.

Cells: These are the production units in the model. They take input tokens and produce output tokens. A hospital cell is an example. It takes input tokens, such as electricity, water, and medicines, and produces one output token, patients treated.

Channels: These are the connecting elements in the model. They receive output tokens form production cells and transport them as inputs to other cells.

Distributors: These are the allocation units in the model. They map the detailed topology of the infrastructure into the i2Sim model. Also, distributors are the decision elements in the i2Sim model if resources allocation is desirable.

Aggregators: These are the additive elements in the i2Sim model. They combine two or more outputs of the same token into one channel.

The i2Sim model is interfaced with external infrastructures that are not included in the model, using source and sink elements. Any cell in the model can have many input tokens with different types but produces only one output token. A distributor has one input and multiple outputs of the same token type. An aggregator has multiple inputs and one output of the same token type. A conceptual i2Sim cell model is shown in Figure 2.

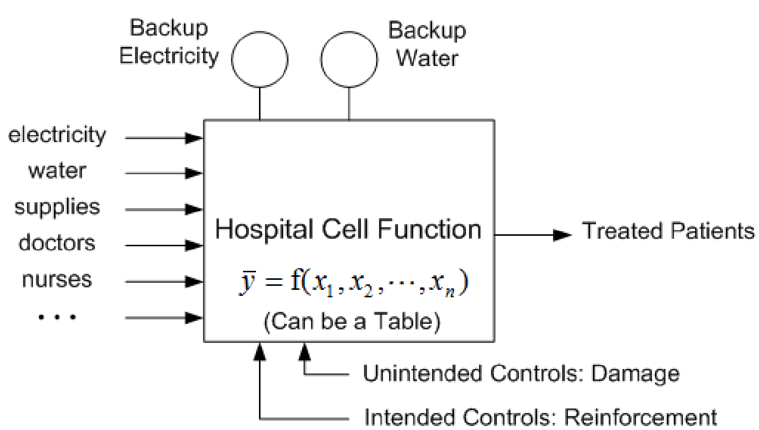
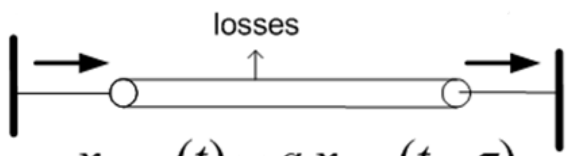


Figure 2. A conceptual i2Sim cell model [6].

3.2 i2Sim Models

The i2Sim model consists of number of cells, channels, distributors, aggregators, sinks and sources. The cell model shown in Figure 2 describes the relationship between inputs and outputs. This model is an extension of the Leontief input-output model [13] to represent the interdependencies among multiple infrastructures. The channel model shown in Figure 3 describes a transportation function with a time delay and losses.



$$x_{arrive}(t) = a\, x_{send}(t-\tau)$$

Figure 3. A conceptual i2Sim channel model [6].

In the i2Sim framework, the possible output of cells and channels are discretized into five levels as shown in Table 1. A colour code is used to show the output level of the production cell during the simulation. Each colour corresponds to an output level measured by its operability level in percentages of its rated output. The concept of output discretization into a finite number of levels reduces the dimensionality of the problem especially when simulating large complex systems. Cells and channels functions, along with the distributor and aggregator equations, set up the overall infrastructures conditions. These conditions are represented by a system of discrete time equations that are solved by the i2Sim simulator. The solution of this system of equations gives the availability of input tokens to every infrastructure.

Table 1. i2Sim discritized operability levels [6].

Colour	State
	100 %
	75 %
	50 %
	25%
	0 %

4. Critical Infrastructures Ranking

A ranking list of critical infrastructures is extremely useful in planning emergency management investments. As a basic concept, the importance of a system component depends on the impact caused by its failure or absence from the system. Therefore, a ranking approach can be developed based on measuring the impact of a failure of one (or more) critical infrastructure in a modelled area. The impact (consequence) needs to be quantified and an importance measure is used to rank the critical infrastructures. Different importance measures can be developed based on the methodology and models used in the analysis. The methodology proposed in this paper can be described as follows:

1) Define the critical infrastructures to be included in the analysis

2) Build the i2Sim model for the infrastructures under consideration

3) Generate a failure scenario in which one of the considered infrastructures is affected.

4) Evaluate the consequence of that failure and then calculate the importance measure (IM). The importance measure is defined as the relative performance drop after the failure. It can be expressed as follows:

$$IM = (Performance_{normal} - Performance_{failure})/Performance_{normal} \quad (1)$$

5) Repeat step 3 for all the infrastructures considered in the ranking.

6) Generate the ranking list according to IM values.

The failure scenarios are represented by failure sets. Each set has the infrastructure components to be affected. The number of possible failure sets increases rapidly as the set size increases and is given by:

$$\frac{k!}{(k-n)!n!} \quad (2)$$

Where k is the total number of components in the model and n is the size of the failure set. For instance, a model with 100 components has a 161,700 failure sets of size 3. Enumerating all possible failure sets is impractical. One possible way is to consider only failure sets with high failure probabilities. In this paper, only failure sets of sizes 1, 2, and 3 are considered. Also, the use of i2Sim modelling approach allows for considering two failure modes: total failure (0% operability level) and partial failure (50% operability level). Such consideration is not possible in many of the topological models used in the literature.

5. Test Case

In this section, the proposed methodology is applied to a test case representing a large city. The i2Sim model for this city is shown in Figure 4. The model was developed based on real data for the infrastructures and was collected in previous works. The selected infrastructures for the study are 2 hospitals, 4 power substations, 1 water pump station, and 2 non-critical infrastructures. The two non-critical infrastructures are combinations of some residential and commercial buildings. Every infrastructure is represented by an i2Sim production cell. It is important to note that the i2Sim model represents a high level abstraction of the real infrastructure. The input-output function of each cell provides the necessary behavioural information for measuring the impact on the modelled infrastructures. The topological information is captured by the arrangements of channels, distributors and aggregators as shown in Figure 4.

In the context of disaster management, saving lives has the highest priority. Therefore, the total output of the two hospitals is chosen to be the performance measure for this test case. The output of the hospital model in i2Sim is the rate of treating patients, i.e. number of treated patients per hour. The importance measure is calculated as the drop in the hospitals output normalized to the rated output.

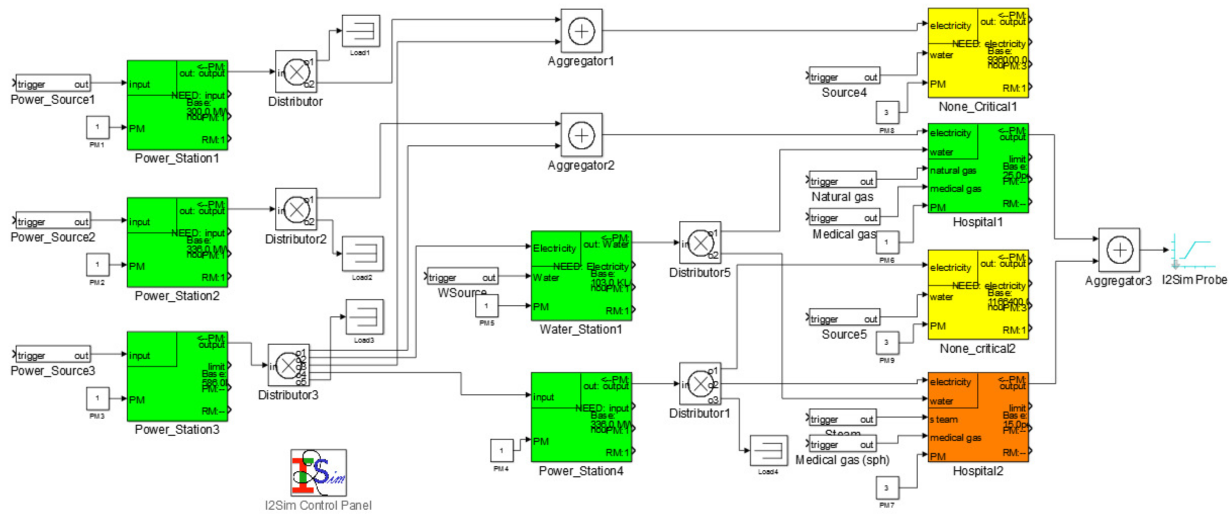


Figure 4. i2Sim model for the test case.

Three sizes of failure sets are considered: 1, 2, 3. the total number of combinations is 9 for Size-1 + 36 for Size-2 + 84 for Size-3 = 129 failure sets. For every failure set, two failure modes are tested: total failure (100% damage) meaning that the infrastructure is totally out of service, and partial failure (50% damage) meaning that the infrastructure is affected by the disaster but it can still provide some output. An example of the partial failure mode is the failure of one main transformer in a power substation that normally uses two main transformers. It is possible to test more partial failure modes using the i2Sim discretized operability levels as described in Section 3.2. However, only one partial failure mode (50% damage) is considered in this paper.

The results for the total failure mode for the top ranking failure sets are shown in Table 2. It is observed that the top two critical infrastructures appear in the top of size-1 sets with IM=1, meaning that total damage to any of these two infrastructures will completely affect the two hospitals. Even though each hospital has two alternative power supplies, from two different power substations, as shown in Figure 4, Power Substation 3 can cause a major interruption to both hospitals. This can be attributed to the interdependency phenomena since it also supplies the only water pumping station in the system.

The results for failure sets of size 2 and 3 show that the ranking are dominated by the presence of the two critical infrastructures: Power Station_3 and Water Station. We know that they are critical in themselves from the results of failure sets of size-1. Therefore, they cause the highest impact regardless of which other infrastructure fails with them. Failure sets containing these two critical infrastructures can be filtered out to show the ranking of other important sets. In fact, some less critical infrastructures can cause tremendous damage if they fail simultaneously. Consider, for instance, the 6th failure set in the size-2 list in which Power Station_4 and Hospital_1 can cause a major drop in the system performance if they fail together.

Table 2. Ranking of failure sets for 100% failure mode.

Rank	Size = 1		Size = 2		Size = 3	
	Failure Set	IM	Failure Set	IM	Failure Set	IM
1	Water Station	1	{Water Station, None Critical2}	1	{Water Station, None Critical1, None Critical2}	1
2	Power Station3	1	{Water Station, None Critical1}	1	{Water Station, Hospital2, None Critical2}	1
3	Hospital1	0.625	{Water Station, Hospital2}	1	{Water Station, Hospital2, None Critical1}	1
4	Power Station2	0.45	{Water Station, Hospital1}	1	{Water Station, Hospital1, None Critical2}	1
5	Power Station4	0.375	{Power Station4, Water Station}	1	{Water Station, Hospital1, None Critical1}	1
6	Hospital2	0.375	{Power Station4, Hospital1}	1	{Water Station, Hospital1, Hospital2}	1
7	Power Station1	0	{Power Station3, Water Station}	1	{Power Station4, Water Station, None Critical2}	1
8	None Critical2	0	{Power Station3, Power Station4}	1	{Power Station4, Water Station, None Critical1}	1
9	None Critical1	0	{Power Station3, None Critical2}	1	{Power Station4, Water Station, Hospital2}	1
10	-	-	{Power Station3, None Critical1}	1	{Power Station4, Water Station, Hospital1}	1

The results for the 50% failure mode are shown in Table 3. It can be seen that the two critical infrastructures: Power Station_3 and Water Station are still in the top of the ranking of size-1 sets. However, the partial failure mode shows a difference in the criticality, 0.575 for Power Station_3 and 0.525 for Water Pump Station. These results suggest that different failure modes can result in different criticality rankings. This also can be seen in the comparison between the rankings of the two failure modes shown in Figure 5.

Table 3. Ranking of failure sets for 50% failure mode.

Rank	Size = 1		Size = 2		Size = 3	
	Failure Set	IM	Failure Set	IM	Failure Set	IM
1	Power Station3	0.575	{Power Station4, Hospital1}	0.75	{Power Station4, Hospital1, Hospital2}	0.825
2	Water Station	0.525	{Power Station3, Hospital1}	0.75	{Power Station3, Hospital1, Hospital2}	0.825
3	Hospital1	0.5	{Hospital1, Hospital2}	0.75	{Power Station2, Power Station3, Hospital1}	0.825
4	Power Station2	0.325	{Water Station, Hospital1}	0.7	{Power Station2, Power Station3, Hospital2}	0.775
5	Power Station4	0.25	{Power Station2, Power Station3}	0.7	{Water Station, Hospital1, Hospital2}	0.75
6	Hospital2	0.25	{Power Station3, Hospital2}	0.65	{Power Station4, Water Station, Hospital1}	0.75
7	Power Station1	0	{Water Station, Hospital2}	0.575	{Power Station4, Hospital1, None Critical2}	0.75
8	None Critical2	0	{Power Station4, Water Station}	0.575	{Power Station4, Hospital1, None Critical1}	0.75
9	None Critical1	0	{Power Station3, Water Station}	0.575	{Power Station3, Water Station, Hospital1}	0.75
10	-	-	{Power Station3, Power Station4}	0.575	{Power Station3, Power Station4, Hospital1}	0.75

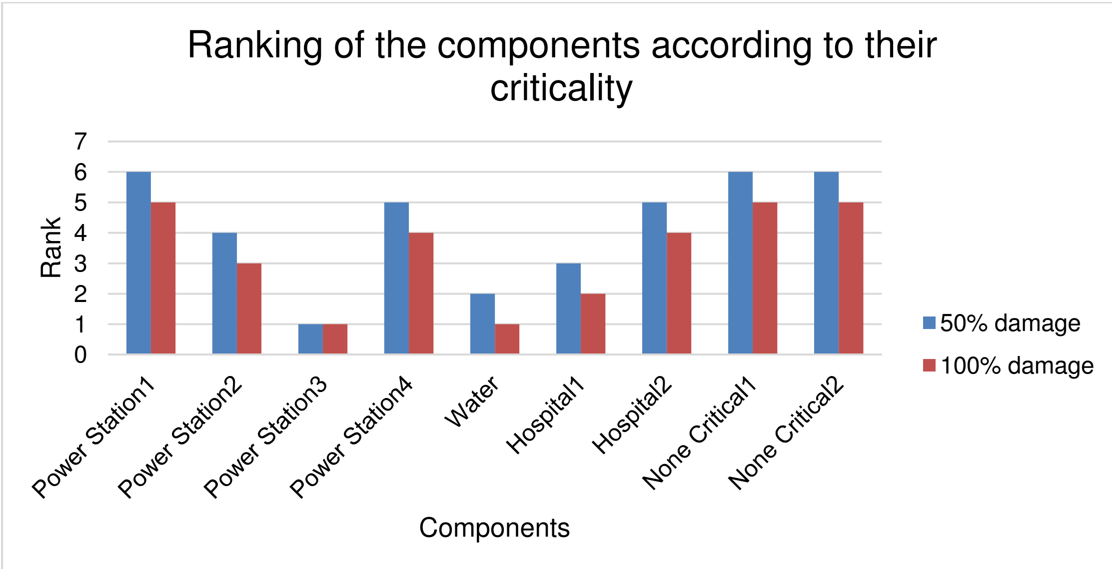


Figure 5. Comparison of the rankings in two different failure modes.

6. Conclusion

Critical Infrastructure Protection (CIP) is one of the significant issues nowadays. Defining priorities for CIP planners is a challenging task. In this paper, we propose a methodology that facilitates the identification and ranking of critical components in multiple infrastructures. Using this methodology, emergency management agencies can direct their investments to the most critical components in the considered locations. The modelling approach in the proposed methodology provides several advantages. First, it considers the interdependent relationships between different infrastructures. Also, it allows for simulating the functional behaviour of the modelled infrastructures in contrast to the topological models that only show the links between them. In addition, different failure modes can be simulated which expands the scope of the analysis.

Analysis of the test case reveals some interesting results. The interdependencies among the critical infrastructures play important role in the ranking process. For example, the importance of one of the power stations increases because it powers a water station that supplies water to the hospital. Also, when different failure modes are considered, the ranking changes. This observation will be investigated further in future work. Another direction for our future work is the consideration of failure probabilities in the analysis to assess the risk associated with each failure set.

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