Identifying Critical Infrastructure Interdependencies for Healthcare Operations during Extreme Events

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Abstract. Critical infrastructures provide vital functions for sustaining our society, and failure in a critical infrastructure leads to massive economic losses and even human casualties. As such, protecting critical infrastructure from disasters is the highest priority task for all countries. One of the key challenges is to understand and manage interdependencies between critical infrastructures. Failure in one infrastructure can cause unanticipated disruptions in others causing a cascade, and the degree and extent of damage could far exceed the initial prediction. In this paper, a critical infrastructure is viewed as a function that satisfies relevant need from a society. In fulfilling its function, a critical infrastructure may rely on resources and services that other infrastructures provide. With this view, we propose a conceptual definition for interdependency between critical infrastructures: interdependency via demand and capability. Using this definition, an interdependency matrix for critical infrastructures can be constructed, with which potential cascading scenarios can be identified. For an illustration purpose, a pilot interdependency matrix at an abstract level is presented, and a few cascading scenarios are identified and compared to those reported in prior literatures on real cases.

Keywords: infrastructure interdependency modeling, healthcare infrastructure, rare disaster management, critical infrastructure protection, cascading failure.

1 Introduction

Every year, many disasters, natural and man-made, bring catastrophic losses worldwide. In 2011, there were 332 reported natural disasters which caused more than 30,770 deaths and 244.7 million victims at a cost of US$ 366.1 billion [1]. In order to reduce the scale of economic losses and human casualties, it is very important to protect critical infrastructures of a society, and much research is dedicted to the topic of critical infrastructure protection (CIP) [2]. Critical infrastructures are vital systems and assets of a society that must be protected [3]. This paper tackles the issues of modeling interdependencies in large, complex infrastructure networks.

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1.1 Definition of Interdependencies and Cascading Failures

For most part, research on CIP tends to center around the modeling of individual infrastructure. To date, few studies have attempted to consider interdependencies between critical infrastructures. Rinaldi et al. [4] defines interdependency as a bidirectional relationship between infrastructures. Due to the interdependencies between critical infrastructures, failures in one infrastructure can cause unanticipated disruptions in others and accordingly, the degree and extent of damage may far exceed the initial expectations from the initiating event [5]. This can be referred to as "cascading failure". As infrastructures of a modern society have become increasingly interdependent, it is becoming more common to face these unanticipated cascading failures, so-called rare disasters.

1.2 Network-Based Interdependency Modeling

Although research on identifying rare disasters is still in its early stage, a number of U.S. national laboratories, including Los Alamos National Laboratory and Argonne National Laboratory, and research programs at universities have taken on this role. They have tried to understand the behavior of infrastructures by developing their own modeling and analysis tools [6]. Literature on this field fall into several categories: Agent-based modeling [7-8], System Dynamics [9-10], Input-output Model [11-14], and Petri-net [15-16].

As far as modeling is concerned, network-based modeling approaches form the basis for most researches. In network-based modeling, interlinked infrastructures are modeled as a network of nodes and edges, where nodes represent individual infrastructures and edges represent their relationship. National Infrastructure Simulation and Analysis Center (NISAC), a program within the U.S. department of homeland security (DHS), has applied network theory in an attempt to clarify interdependencies between eighteen critical infrastructure sectors. There are several types of NISAC network-based models: network flow models, system dynamics models, agent-based models and combinations of these models [17].

Critical Infrastructure Modeling System (CIMS) proposed by Dudenhoeffer [7] uses an agent-based modeling approach (ABM), where each physical infrastructure is modeled as an agent. The physical entities are displayed as nodes in infrastructure networks. Min et al. [9] developed a system dynamics model employing a functional modeling methodology, IDEF0, in order to show material flow relationships among infrastructures. Unlike other network-based approach, they model functions of infrastructures, instead of existing physical entities.

In this paper, a critical infrastructure is viewed as a function that satisfies relevant need from a society. In fulfilling its function, a critical infrastructure may rely on resources and services that other infrastructures provide. With this view, we propose a conceptual definition for interdependency between critical infrastructures: interdependency via demand and capability. Using this definition, an interdependency matrix for critical infrastructures can be constructed, with which potential cascading scenarios can be identified. Our framework is similar to IDEF0 model in that it focuses on each infrastructure's function. The main difference between our framework and IDEF0 [9] is the definition of function and the classification of dependency edges. This would be explained further in section 2.

1.3 Significance of Identifying Cascading Scenarios for Healthcare Operations

Since healthcare is directly related to human survival, it is important to guarantee the continuity of healthcare services, especially in extreme events. Healthcare operations are inevitably affected by disruptions in other infrastructures, and we certainly need to identify cascading scenarios showing how failures cascade through various infrastructures' functionalities and finally affect the provision of healthcare. So far, very little has been done in this direction. Arboleda et al. [18-19] used a network to represent interdependencies. However, they only dealt with physical healthcare facilities and lacked practical usage in other entities. Using the conceptual definitions and ensuing framework proposed in this paper, we represent infrastructure interdependencies related to healthcare domain. The identified cascading scenarios for healthcare operations of our framework will be presented in section 3.

2 Overview of Proposed Framework

This framework is motivated by the need for infrastructure interdependency networks. Although the above mentioned literatures deal with this topic, they primarily focused on existing physical entities [7, 18-19]. A few of them looked into this topic with top-down approach, functional modeling in terms of nodes [9], but did not define the edges according to the characteristics of infrastructure interdependencies. Thus, we propose a framework with both functional modeling and redefined dependency edges.

In section 2.1, we will define nodes and classify dependency edges between infrastructures into two types – Capability (C) and Demand (D). In section 2.2, an interdependency matrix for critical infrastructures will be constructed. Based on the completed matrix, the benefits of the framework will be discussed in section 3.

2.1 Infrastructure as a Function and Classification of Dependencies

In IDEF0 diagram, a function or activity has four types of edges connected to it. There are three incoming edges (input, control, mechanism) and one outgoing edge (output). A function in the IDEF0 diagram serves to transform or change the inputs in some way in order to create the outputs. Based on this IDEF0 representation, Min et al. [11] used the diagram to describe the material flows among infrastructures. We also model an infrastructure as a function, with a slightly different perspective. A critical infrastructure is viewed as a function that satisfies relevant need from a society. Thus, an infrastructure is defined as a function in the context of 1) its purpose, i.e., the need or demand from a society, 2) resources or services it uses, and 3) outputs it produces (Fig. 1). With this notion, an infrastructure may affect other infrastructures by 1) influencing their needs or 2) failing to provide necessary resources/services, thereby affecting their capability. In short, an infrastructure as a function serves to meet its demand with its capability. The failure of a function means that the function could not meet its demand with its capability. Accordingly, a function could be affected by other functions in two possible ways: the capability or the demand. We call each of these dependences as C-dependency and D-dependency (Table 1). Fig. 2(a) depicts these relationships.

For a simpler representation, we use graph representation of an infrastructure network. A node in a graph represents a function that an infrastructure serves, and a node can have two types of directed edges to indicate the type of dependency. Interdependencies are made up of multiple dependencies [4], so the two types of dependency are basic elements of our interdependency modeling framework.

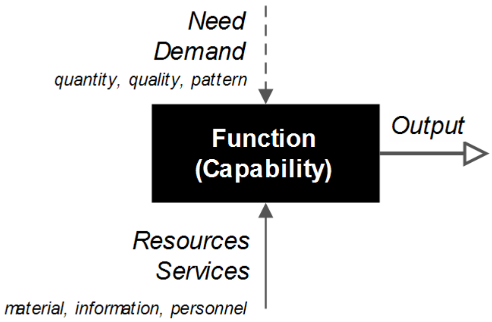

Fig. 1. In this paper, a *function* is defined by the role it serves in the middle of many interacting functions. The role of a function (*the exact quantity, quality and pattern of the demand)* is determined by the need of other functions. The ability of a function *(the capability)* may rely on *resources and services* that other functions provide.

Table 1. The classification of dependencies between *function A* and *function B*

Classification	Definition
C-dependency	'C-dependency exists from function A to function B' means that function A affects the *capability* of function B.
D-dependency	'D-dependency exists from function A to function B' means that function A affects the *demand* of function B.

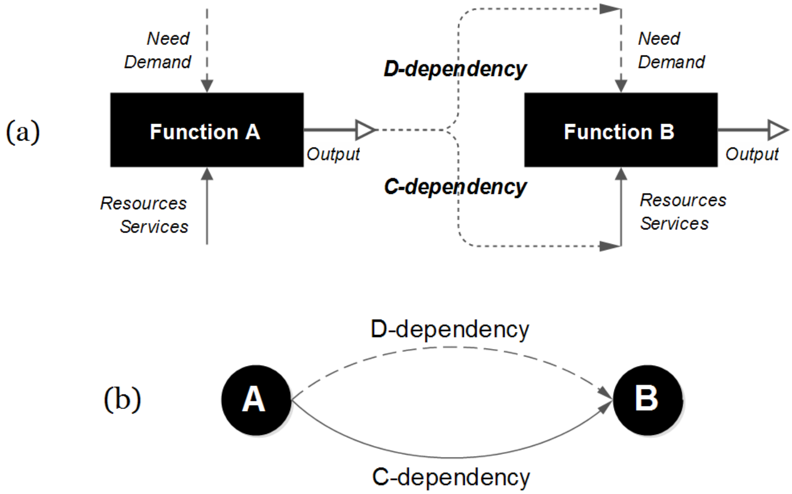

Fig. 2. (a) *Function B* may depend on *function A* in two different ways, depending on which component of *function B* was affected by the output of *function A*. (b) An edge is unidirectional and represents a specific type of dependency between two function nodes.

It is worthwhile to note that the definition and the classification of dependencies found in the previous literatures, shown in Table 2, imply that infrastructures are physical entities. Thus, while some of the concepts share common aspects with our dependency definition, many of them are not applicable to our case where infrastructures are modeled as a function. One such example is geographic or geospatial dependency between two infrastructure facilities [4].

Table 2. Previous classifications of dependencies between two nodes (*physical entities*)

Literature	Classification of dependencies
Rinaldi et al. [4]	Geographic, Physical, Cyber, Logical
Brown [17]	Geographic, Physical, Logical
Buhne et al. [20]	Requires-dependency, Exclusive-dependency, Hints-dependency, Hinders dependency
Dudenhoeffer et al. [7]	Physical, Geospatial, Societal, Policy/Procedural, Informational
Zhang et al. [21]	Physical, Functional, Budgetary, Market, Information, Environmental

2.2 Construction of an Interdependency Matrix

Based on the nodes and edges we defined in section 2.1, we will construct an interdependency matrix which can be transformed into a network.

Determining Infrastructure Nodes – Construct an Empty Matrix. Among eighteen critical sectors (CIKR) defined by the U.S. department of Homeland Security [22], we chose several relevant sectors and regrouped them into five infrastructures as shown in Fig. 3. We will occasionally call them using the abbreviation of their name: H, E, T, I[1], W.

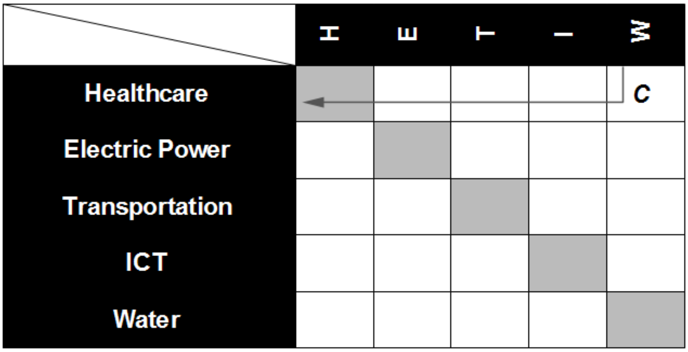

Fig. 3. The rows and columns of the interdependency matrix shows the infrastructure functions (*H, E, T, I, W*) that we chose to include in the network. The alphabet *C* written at the first row means that *there exists a C-dependency from function W to function H*. In other words, Water infrastructure affects the capability of Healthcare.

Determining Dependency Edges – Filling in Blanks in the Matrix. Determining which dependency exists from the column node to the row node, deserves our full attention and thoroughness. We need to ask ourselves whether any one of two dependencies exists between two nodes. Table 3 illustrates how to determine the existence of dependency types between two functions through a series of questions.

Table 3. The existence of C-dependency and D-dependency

Dependency Type	**How to determine the existence of each dependency type between two functions?**
C-dependency	We can determine whether or not 'C-dependency exists from function A to function B' by asking the following question: "Does function A *provide the resources or services* required for the capability of function B?" If the answer is *no*, then C-dependency from A to B does not exist. If it is *yes*, C-dependency from A to B exists. For example, Transportation infrastructure affects healthcare infrastructure via C-dependency because emergency medical service function requires proper functioning of transportation infrastructure.

[1] ICT : Information and Communications Technology.

Table 3. (*continued*)

D-dependency	We can determine whether or not 'D-dependency exists from function A to function B' by asking the following question: "Does function A *affect the demand* of function B?" If the answer is *no*, then D-dependency from A to B does not exist. If it is *yes*, D-dependency from A to B exists. For example, power outage in electricity infrastructure may cause disruption in self-care at patients' home thereby increasing demand for healthcare infrastructure.

3 Identified Cascading Scenarios for Healthcare Operations

As an illustration, a pilot interdependency matrix at an abstract level is presented (Fig. 4), and cascading scenarios from electric power to healthcare are identified (Table 4) and compared to those reported in prior literature on real cases. A few researches have

	H	E	T	I	W
Healthcare		CD	CD	CD	CD
Electric Power	C		C	CD	C
Transportation	CD	CD		CD	D
ICT	C	CD	C		D
Water	C	C	C	CD	

Fig. 4. The completed interdependency matrix contains the information of C and D dependencies

Table 4. The list of identified cascading scenarios (from E to H) *based on C and D-dependency*

Order	**How does failure in electric power cascade to healthcare?**		
1	E-H		
2	E-T-H	E-I-H	E-W-H
3	E-T-I-H	E-T-W-H	E-I-T-H
	E-I-W-H	E-W-T-H	E-W-I-H
4	E-T-I-W-H	E-T-W-I-H	E-I-T-W-H
	E-I-W-T-H	E-W-T-I-H	E-W-I-T-H

tried to identify those cascading scenarios by analyzing the data of previous power outages. Prezant et al. examined the effects of August 2003 blackout in the United States and Canada [23] on New York City's healthcare system [24]. Chang et al. [25] analyzed the data for the power outage consequences in the 1998 Ice Storm in Canada and identified impacted systems.

[E-H] – Direct Cascade from Electric Power. Imagine how easily the *capability* of healthcare (e.g., operating room or intensive care unit) can be affected. Chang et al. [25] provided more examples: medical staff taking the stairs due to malfunctioning elevators, patients tying up beds (refusing to return to blacked-out homes), hospitals calling for volunteers with no medical experience. On the other hand, Prezant et al. [24] gives an example that the *demand* of healthcare is affected by power outage: increased patients (especially respiratory patients due to electrically powered respiratory device failures) and exceptionally high call volume for 911.

[E-T-H] – Cascade through Transportation. The *capability* of transportation was affected in the power outage of 1998 Ice Storm [25]: traffic lights went off, metro stations closed and gas stations unable to pump fuel. The 2003 blackout [24] also caused transportation failure and healthcare support (*capability*) was not delivered to an increasing volume of patients (*demand*).

[E-I-H] – Cascade through ICT. Communication was the most time consuming problem in the power outage of 1998 Ice Storm [25]. Emergency lines became flooded, affecting the *capability* of ICT. Without ICT's help, without computers (*capability*), it was impossible to access vital information needed in healthcare.

The real cases from two previous power outages matched with simple cascading scenarios (e.g., [E-H], [E-T-H], [E-I-H] and [E-W-H]), but cascading scenarios going through more than two infrastructures could not be identified. This is because the prior researches [24, 25] focused on the impact and extent of cascading failures instead of the cascading process. Even though our framework is not based on the data of previous disasters, it can generate, by thought-experiment, the same scenarios as other researches. On top of that, we could come up with even more complicated scenarios like [E-I-T-W-H] based on the interdependency matrix.

[E-I-T-W-H] – Cascade through More Than Two Infrastructures. From other researches [24, 25], we got real examples of simple cascading scenarios like [E-I-H], [E-T-H], [E-W-H]. Based on those examples, we could deduce that much more complicated scenarios (e.g. [E-I-T-W-H]) could have been occurring simultaneously. It can be explained by using the examples in [25]. Firstly, ICT was affected by power outage. This resulted in a cut of electronic communications, and unknown road conditions. As transportation infrastructure's capability was affected, bottled water supplies to communities could not be delivered. Finally, because the capability of water infrastructure was affected, many shelters and other healthcare facilities were negatively affected.

The exhaustiveness of the scenarios in the prior researches [24, 25] cannot be guaranteed because investigating the cascading failures already happened in earlier events allows limited imagination. On the other hand, the exhaustiveness of identified cascading scenarios in this paper (Table 4) can be guaranteed on the basis of C- and D- dependencies. Especially, checking the existence of D-dependency is highly advantageous for an exhaustive enumeration of possible cascading scenarios. Table 5 shows the cascading scenarios identified from only C-dependency. It shows that many scenarios with high order (e.g., [E-W-T-H], [E-W-I-H], [E-T-W-I-H], [E-I-W-T-H], [E-W-T-I-H], [E-W-I-T-H]) were omitted from Table 4. Thus, we can say with confidence that our framework is highly beneficial in that it saves our efforts to analyze massive data.

Table 5. The list of identified cascading scenarios (from E to H) based on *only C-dependency*

Order	**How does failure in electric power cascade to healthcare?**		
1	E-H		
2	E-T-H	E-I-H	E-W-H
3	E-T-I-H	E-T-W-H	E-I-T-H
	E-I-W-H		
4	E-T-I-W-H	E-I-T-W-H	

4 Conclusion

Disasters have a big influence and will continue to impact our infrastructures. It is in everyone's interest to understand how we can manage them effectively and efficiently. One of the key challenges is to understand and manage interdependencies between critical infrastructures. In this paper, a critical infrastructure is viewed as a function that satisfies relevant need from a society. An infrastructure may affect other infrastructures by 1) influencing their needs or 2) failing to provide necessary resources/services, thereby affecting their capability. With this view, we propose a conceptual definition for interdependency between critical infrastructures: interdependency via demand and capability. Using this definition, an interdependency matrix for critical infrastructures can be constructed, with which potential cascading scenarios can be identified.

The strengths of the framework come from the simplicity of construction and the exhaustiveness of redefined nodes and edges. It gives an opportunity to identify cascading scenarios thoroughly without handling with massive data. As an illustration, a pilot interdependency matrix at an abstract level was presented, and the identified cascading scenarios were compared to those reported in prior literatures on real cases.

Further studies are needed to explore the dynamics of cascading failure. We are planning to generate a system dynamics model to show cause-and-effect relationships between capabilities and demands of infrastructures. Also, in order to incorporate more detailed level of knowledge of each individual infrastructure, we are going to decompose infrastructures further and conduct a Delphi survey to confirm the existence and the types of dependencies between functions. Consensus-driven edges would make a thorough investigation on critical infrastructures in the Republic of Korea. It is expected to draw meaningful insights on disaster management.

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References

1. Guha-sapir, D., Vos, F., Below, R., Ponserre, S.: Annual Disaster Statistical Review 2011: The Numbers and Trends. CRED, Brussels (2012)
2. Brunner, E.M., Suter, M.: International CIIP Handbook 2008/2009: An Inventory of 25 National and 7 International Critical Information Infrastructure Protection Policies, Center for Security Studies, ETH Zurich (2008)
3. United States Congress, U.S.A. Patriot Act (2001)
4. Rinaldi, S.M., Peerenboom, J.P., Kelly, T.K.: Identifying, understanding, and analyzing critical infrastructure interdependency. IEEE Control Systems Magazine 21, 11–25 (2001)
5. Holt, M., Campbell, R.J., Nikitin, M.B.: Fukushima Nuclear Disaster. In: Congressional Research Service 7-570 (2012)
6. Pederson, P., Dudenhoeffer, D., Hartley, S., Permann, M.: Critical Infrastructure Interdependency Modeling: A Survey of U.S. and International Research, Idaho National Laboratory (2006)
7. Dudenhoeffer, D., Permann, M., Manic, M.: CIMS: A framework for infrastructure interdependency modeling and analysis. In: Proceedings of 2006 Winter Simulation Conference, pp. 478–485. IEEE, Piscataway (2006)
8. Lee, E.E., Mendonca, D., Mitchell, J.E., Wallace, W.A.: Restoration of services in interdependent infrastructure systems: A network flows approach. IEEE Transactions on Systems, Man, and Cybernetics – Part C: Applications and Reviews 37(6) (2007)
9. Min, H.-S.J., Beyeler, W., Brown, T., Son, Y.J., Jones, A.T.: Toward modeling and simulation of critical national infrastructure interdependencies. IIE Transactions 39(1), 57–71 (2007)
10. Homer, J.B., Hirsch, G.B.: System Dynamics Modeling for Public Health: Background and Opportunities. American Journal of Public Health 96(3) (2006)
11. Marti, J.R., Hollman, J.A., Ventura, C.E., Jatskevich, J.: Dynamic recovery of critical infrastructures: real-time temporal coordination. International Journal of Critical Infrastructures 4(1/2), 17–31 (2008)
12. Haimes, Y.Y., Horowitz, B.M., Lambert, J.H., Santos, J.R., Crowther, K.G.: Inoperability input-output model for interdependent infrastructure sectors. I. Theory and Methodology Journal of Infrastructure Systems 11(2), 67–79 (2005)
13. Rahman, H.M.: Modeling and Simulation of Interdependencies between the communication and information technology infrastructure and other critical infrastructures. A thesis submitted to the University of British Columbia (2009)
14. Rahman, H.M., Armstrong, M., Marti, J.R., Srivastava, K.D.: Infrastructure Interdependencies simulation through matrix partitioning technique. International Journal of Critical Infrastructures 7(2) (2011)
15. Ge, Y., Xing, X., Cheng, Q.: Simulation and analysis of infrastructure interdependencies using a Petri net simulator in a geographical information system. International Journal of Applied Earth Observation and Geoinformation 12, 419–430 (2010)

16. Sultana, S., Chen, Z.: Modeling flood induced interdependencies among hydroelectricity generating infrastructures. Journal of Environmental Management 90, 3272–3282 (2009)
17. Brown, T.: Dependency Indicators. Technical article (ID: SS31) in Wiley handbook of science and technology for homeland security
18. Arboleda, C.A., Abraham, D.M., Richard, J.P., Lubitz, R.: Impact of interdependencies between infrastructure systems in the operation of health care facilities during disaster events. In: Joint International Conference on Computing and Decision Making in Civil and Building Engineering, pp. 3020–3029 (2006)
19. Arboleda, C.A., Abraham, D.M., Lubitz, R.: Simulation As a Tool to Assess the Vulnerability of the Operation of a Health Care Facility. J. Performance of Constructed Facilities 21(4), 302–312 (2007)
20. Buhne, S.G., Halmans, G., Pohl, K.: Modelling Dependencies between Variations Points in Use Case Diagrams. In: Proceeding of 9th International Workshop on Requirements Engineering, pp. 43–54 (2003)
21. Zhang, P., Peeta, S.: Dynamic Game Theoretic Model of Multi-Layer Infrastructure Networks. Networks and Spatial Economics 5(2), 147–178 (2005)
22. U.S. Department of Homeland Security: National Infrastructure Protection Plan: Partnering to enhance protection and resiliency (2009)
23. U.S.-Canada Power System Outage Task Force: Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations (2004)
24. Prezant, D.J., Clair, J., Belyaev, S., Alleyne, D., Banauch, G., Davitt, M., Vandervoorts, K., Kelly, K.J., Currie, B., Kalkut, G.: MPH: Effects of the August 2003 blackout on the New York City healthcare delivery system: A lesson for disaster preparedness. Critical Care Medicine 33(1), 96–101 (2005)
25. Chang, S.E., McDaniels, T.L., Mikawoz, J., Peterson, K.: Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 Ice Storm. Natural Hazards 41(2), 337–358 (2007)