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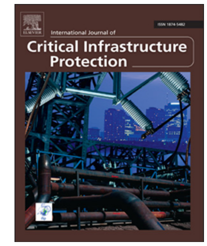

Critical infrastructure dependencies: A holistic, dynamic and quantitative approach

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ABSTRACT

The proper functioning of critical infrastructures is crucial to societal well-being. However, critical infrastructures are not isolated, but instead are tightly coupled, creating a complex system of interconnected infrastructures. Dependencies between critical infrastructures can cause a failure to propagate from one critical infrastructure to other critical infrastructures, aggravating and prolonging the societal impact. For this reason, critical infrastructure operators must understand the complexity of critical infrastructures and the effects of critical infrastructure dependencies. However, a major problem is posed by the fact that detailed information about critical infrastructure dependencies is highly sensitive and is usually not publicly available. Moreover, except for a small number of holistic and dynamic research efforts, studies are limited to a few critical infrastructures and generally do not consider time-dependent behavior.

This paper analyzes how a failed critical infrastructure that cannot deliver products and services impacts other critical infrastructures, and how a critical infrastructure is affected when another critical infrastructure fails. The approach involves a holistic analysis involving multiple critical infrastructures while incorporating a dynamic perspective based on the time period that a critical infrastructure is non-operational and how the impacts evolve over time. This holistic approach, which draws on the results of a survey of critical infrastructure experts from several countries, is intended to assist critical infrastructure operators in preparing for future crises.

1. Introduction

Concerns about the critical infrastructure have increased among governments and citizens with the recognition that societal welfare is highly dependent on the proper functioning of the various critical infrastructure sectors [6,9,41]. Recent disasters, such as the 2011 Fukushima Earthquake and the 2012 Hurricane Sandy, have demonstrated the significant and prolonged consequences of critical infrastructure failures. Whether a critical infrastructure is disrupted by a natural event or by a human-initiated action, the consequences can propagate to other critical infrastructures, potentially resulting in cascading effects that impact all aspects of society [22,9,3].

Some researchers (see e.g., [24,39]) believe that cascading effects due to direct infrastructure dependencies are more probable and more frequent than expected, but the dependencies may not be powerful enough to generate high order cascading effects. Identifying the dependencies involving every critical infrastructure and the consequences that a failure of a specific critical infrastructure may have on other

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critical infrastructures improves the understanding of the critical infrastructure as a "system of systems" and helps design effective responses to future crises.

The study of critical infrastructure dependencies is a challenging task [39]. Despite substantial interest by the research community, it is still an immature, albeit rapid-growing, discipline [4,13,16,31,32]. While numerous researchers have focused on critical infrastructure dependencies (see e.g., [2,3,5,7,10–13,15,21,25,27,29–33,35,38,39,43]), the vast majority of efforts consider individual or a few critical infrastructures, perform qualitative as opposed to quantitative analyses, fail to consider time-dependent (dynamic) behavior and/or rely on limited or artificial data because detailed information about critical infrastructures is not publicly available due to its sensitivity.

Some researchers have, in fact, performed holistic, dynamic and quantitative studies of critical infrastructure dependencies [24,26]. Macaulay [26] has analyzed the normal operating conditions of critical infrastructures and dependencies based on the amount of money that infrastructures pay for products and services delivered by other infrastructures and receive for delivering products and services to other infrastructures. Luiijf et al. [24] have analyzed major events that led to cascading failures affecting more than 10,000 critical infrastructure customers in order to study the frequency of cascading events and identify the triggers. In contrast, this paper attempts to analyze critical infrastructure dependencies regardless of whether or not there was a major incident that affected society and without conducting an economic analysis involving operating conditions. The objective of this research is to identify all existing critical infrastructure dependencies and to analyze the impact suffered by a dependent critical infrastructure over time in a hypothetical situation where another critical infrastructure cannot deliver products and services to the dependent critical infrastructure. This provides assessments of the performance levels of dependent critical infrastructures over time and indications about if and when a failure would cascade to other infrastructures.

Recognizing the limitations of earlier work, this paper seeks to quantify the impact of critical infrastructure dependencies using a holistic and dynamic perspective. The research is based on a survey of critical infrastructure experts from two continents that sought to identify the dependencies between critical infrastructures when failures of different durations in one infrastructure affect another infrastructure. The quantification of infrastructure dependencies can help critical infrastructure operators understand how a failure in a critical infrastructure that prevents it from delivering products and services can affect the performance levels of their own critical infrastructures. Moreover, it can help reduce and manage the effects of critical infrastructure disruptions [43].

2. Background

The critical infrastructures considered in this work are taken from the European Commission's "Green Paper" on the European Programme for Critical Infrastructure Protection [14]. This document specifies 11 infrastructures as being critical: (i) energy; (ii) information and communications technology (ICT); (iii) water; (iv) food; (v) health; (vi) financial; (vii) public and legal order and safety; (viii) civil administration; (ix) transport; (x) chemical and nuclear industry; and (xi) space and research.

The Council Directive 2008/114/EC of the European Union [8] emphasizes the vital role that critical infrastructures play in modern society. It defines a critical infrastructure as "an asset, system or part thereof located in member states which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact on a member state as a result of the failure to maintain those functions."

A national (or regional or international) critical infrastructure is a complex system of interconnected and dependent critical infrastructures [1,19,20,36] because individual critical infrastructures need products and/or services from other critical infrastructures in order to operate normally. Critical infrastructure dependencies are unavoidable and their presence makes individual critical infrastructures and the critical infrastructure as a whole more vulnerable to failure [4,31,42].

Critical infrastructure operators typically understand first order dependencies, which are direct dependencies of their own critical infrastructures on other critical infrastructures, and they are cognizant of the vulnerabilities posed by these dependencies. However, although detailed information about individual critical infrastructures and their elements can be obtained, the understanding of critical infrastructure dependencies is limited because of the complexity and interconnectivity of critical infrastructures. In particular, critical infrastructure operators have very limited understanding about higher order dependencies [34].

Fig. 1 helps clarify the notions of a first order dependency and a higher order dependency. In Fig. 1(a), A has a first order dependency on B due to products and services delivered to it by B. Similarly, B has a first order dependency on C, and C has a first order dependency on B. Therefore, as shown in Fig. 1(b), A has a second order (transitive) dependency on C due to the direct dependencies of A on B, and B on C. Therefore, if C stops working and B does not receive products and services from C, then B may not be able to deliver products and services to A. Because higher order dependencies are not direct, they are often difficult to discern. Moreover, their effects may not be immediate, which significantly complicates the tasks of identifying the cause of a failure and mitigating its effects.

Because of the complexity of critical infrastructure dependencies, the vast majority of researchers have conducted analyses of limited numbers of critical infrastructures (see e.g., [3,7,10,12,13,15,21,25,27,29–33,35,38,43]). Several researchers [2,5,11,24,26] have attempted to model dependencies in all the

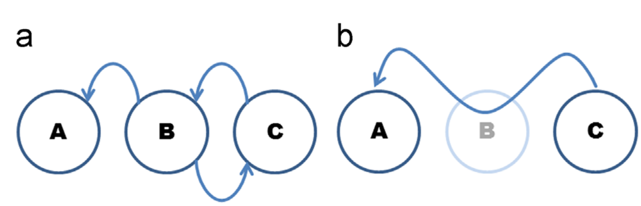

Fig. 1 – First and second order dependencies between critical infrastructures.