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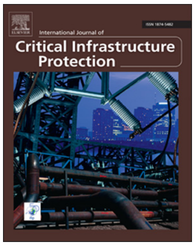

Quantitative evaluation of the synergistic effects of failures in a critical infrastructure system

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ABSTRACT

A critical infrastructure is a complicated system whose failure (in whole or in part) has a significant impact on national interests, including security, the economy and basic human needs. The system consists of relevant sectors, elements and their mutual linkages. In order to study critical infrastructures, it is necessary to apply a systems approach based on cross-sectoral evaluation and research into the linkages between the individual critical infrastructure sectors. Specifically, it is necessary to describe the individual vertical and horizontal levels of each critical infrastructure and the associated linkages. From this point-of-view, a critical infrastructure is embedded within the broader context of emergencies and enterprises, representing a compact and mutually-interconnected system.

This paper focuses on quantitatively assessing the impacts of critical infrastructure failures. It presents a theory of synergistic linkages, their levels and the synergistic effects due to the joint action of impacts, which increase the overall impact on the critical infrastructure and on society. The concepts are formalized in the SYNEFIA methodology, which is applied in a case study involving the critical infrastructure of the Czech Republic. In particular, the methodology is applied to determine the synergistic effects of disruptions to multiple sub-sectors of the Czech infrastructure.

1. Introduction

Advanced societies require infrastructures [4] for their smooth functioning as well as to enhance general welfare and continued development. The purpose of critical infrastructures is to effectively and rapidly distribute energy, commodities and services to recipients (i.e., society) through its sectors, elements and linkages [3]. However, infrastructures all over the world are constantly being threatened by a broad spectrum of interacting anthropogenic and natural dangers [32]. An activated threat can cause a failure of a component or function of an infrastructure. Admittedly, such an event is not very likely, but its impact could be enormous [17]. The level of unacceptable impacts depends on the

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severity of the failure, its cause (i.e., character of the threat) and the criticality of the affected elements or sectors. Such impacts are often expressed in terms of economic losses, number of people affected, size of the affected region and other factors that fall into three basic categories: (i) critical proportion; (ii) critical time; and (iii) critical quality [11]. When the threshold values of the impacts (i.e., sectoral and cross-cutting criteria) are exceeded, the corresponding infrastructure sectors and their elements are deemed to be critical; taken together, they constitute the critical infrastructure [10].

The importance of critical infrastructure protection was first highlighted by the United States in 1995. Over the years, critical infrastructure protection activities were initiated by other countries – Canada in 1998 and the United Kingdom, Sweden and Switzerland in 1999. Since the infamous attacks of September 11, 2001, many European countries have defined their critical infrastructure assets and launched critical infrastructure protection efforts.

In the National Infrastructure Protection Plan of 2013 [31], the U.S. Department of Homeland Security defined the critical infrastructure as “systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters.” The Australian Government [1] defines critical infrastructure as “those physical facilities, supply chains, information technologies and communication networks which, if destroyed, degraded or rendered unavailable for an extended period, would significantly impact on the social or economic wellbeing of the nation or affect Australia's ability to conduct national defense and ensure national security.”

At the European Union level, the term critical infrastructure is defined in two key documents. The first is the Green Paper on the Programme of Critical Infrastructure Protection [7], which was published in 2005 by the European Commission. The second is the Council Directive on the Identification and Designation of European Critical Infrastructures and on the Assessment of the Need to Increase Their Protection [10], which was published as a follow-up to the Green Paper in 2008. The council directive defines 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 in a Member State as a result of the failure to maintain those functions.” The directive leaves the responsibility for critical infrastructure protection to national authorities.

Critical infrastructures are complex. In effect, critical infrastructures and their dependencies form a system of systems [20,25]. The overall critical infrastructure has an obvious hierarchy, consisting of individual sectors such as energy and transportation, along with their linkages [25]. The sectors consist of elements that are considered to be a basic part of the system. Currently, it is possible to distinguish two basic methodological approaches for the risk assessment of critical infrastructures. The first is the sectoral approach, where each sector is assessed separately with its own risk assessment methods. The second is the systems approach, where individual critical infrastructure sectors are deemed to be interconnected networks.

Research in the critical infrastructure protection field [8,9] should improve the fidelity and precision of simulation tools for modeling the impact of critical infrastructure malfunctions [14]. The research should also be extended to the synergies and synergistic effects of infrastructure failures. Dynamic functional modeling [29] is a promising approach that can consider synergistic effects. However, it is currently used to simulate the systemic impacts on critical infrastructures (i.e., basic impacts without synergies) and does not support the modeling and simulation of synergistic effects.

2. National critical infrastructure system

The hierarchic arrangement of a national critical infrastructure system has three levels that constitute a vertical classification:

- System level.
- Sector level.
- Element level.

The system level is the basic classification of a critical infrastructure according to its functions. This level comprises: (i) the technical infrastructure and (ii) the socioeconomic infrastructure. For example, the technical infrastructure in the Czech Republic includes the energy, transport, water supply, food processing, agriculture, industry, and communications and information systems sectors. The socioeconomic infrastructure in the Czech Republic includes health care, financial and currency markets, emergency services and public administration. There are significant dependencies between the two types of critical infrastructure. For instance, all the socioeconomic sectors require the commodities produced by the technical infrastructure sectors. The technical sectors depend on the socioeconomic sectors, especially in crisis situations.

The sector level is made up of the individual sectors of a critical infrastructure (e.g., energy and water supply). This level represents the classification of actual sectors of the critical infrastructure and their linkages.

The individual components that form the element level are the basic building blocks of the system hierarchy of the sectors. The elements are relevant to the system due to the impacts produced by their failure. The elements can be classified into four categories based on their potential impacts [26]. Table 1 provides a detailed description of the classification.

In addition to the vertical categorization, it is also possible to view a critical infrastructure system with respect to its horizontal linkages. This creates a context with the surrounding processes and operators. The linkages define what impacts a critical infrastructure and what can be affected in the event of a failure. The correlation of the cause–failure–impact scenario