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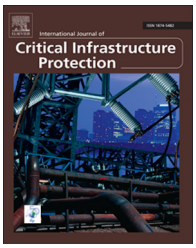

Interdependency-induced risk with applications to healthcare

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ABSTRACT

Developing effective protection, mitigation and recovery measures for critical infrastructures is paramount in the wake of increasing natural and human-initiated hazards, risks and threats. Influencing these measures are interconnections (i.e., interdependencies) among infrastructure systems. Understanding the nature of system interdependencies can play an essential role in minimizing and/or reducing the probabilities and consequences of cascading failures in interdependent systems. This paper discusses the need for policy-makers, infrastructure operators and researchers to consider alternative approaches to formulating risk and enabling solutions to challenging 21st century issues related to interdependent infrastructures. Using the healthcare sector as an example, this paper suggests that identifying the risks associated with maintaining public health goes beyond traditional risk formulation to include the structural complexity brought about by infrastructure interdependencies.

1. Introduction

Often described in relation to decision-making, risk is usually defined in terms of the probability of occurrence of an event and the magnitude of the resulting consequences [1]. However, there are different articulations of risk depending on the context. For example, in an industrial setting, risk is associated with the determination of event sequences and the evaluation of event frequencies and probabilities [2]. In systems analysis, risk is associated with the probabilities of unknown outcomes and uncertainties [3]. In systems engineering, risk is related to technical factors in the system life cycle [4]. Risk perception is also relative to one's position in an organizational setting [5]. While Gheorghe et al. [6] suggest that risk is subjective in nature and therefore a mental construct, Parsons [7] describes risk in terms of "unknown unknowns". Meanwhile, Holton [8] and Knight [9] suggest that risk is associated with uncertainty. The notion of risk also includes significant considerations of human/social, organizational/managerial and policy/political elements

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[10,11]. Hence, Pinto et al. [12] saw a need for a multi-disciplinary approach to risk in our increasingly complex society. While no commonly-accepted definition of risk currently exists, the concepts of uncertainty, unpredictability, complexity and lack of understanding appear to characterize risk [13–16].

Exacerbating the notion of risk in modern society is the nature of critical infrastructures whose destruction can have a debilitating impact on public wellbeing. Modern society increasingly depends on the goods and services provided by critical infrastructures. However, critical infrastructures do not operate as isolated systems [17,18]; instead, they operate as interconnected systems whose state depends on the state of other systems [6,19,20]. Partially because of unprecedented technological advancements and ubiquitous computing, rapid institutional changes, increasing complexity, trans-boundary dependencies and increasing demand for quality services [18], managing risk in the context of critical infrastructures may require a reformulation of the notion of risk to deal with the interdependent nature of critical infrastructures. Pederson et al. [21] suggest that there is a need to develop methods and tools that enable the identification of infrastructure interactions. However, there is a paucity of methods that support risk management in interdependent critical infrastructures, which must operate as integrated wholes.

From a risk perspective, the presence of dependencies, interactions, interdependencies and interconnections among critical infrastructures necessitate a risk analysis approach that goes beyond a single system of interest. This paper suggests that understanding interdependencies in critical infrastructures can be an essential step towards the reformulation of traditional risk and that interdependencies provide a foundation for developing alternative approaches that address essential elements of the field. To fulfill this objective, Section 2 offers perspectives of critical infrastructures and their importance in maintaining public wellbeing. Section 3 discusses emerging areas of concern in the field of critical infrastructures, including vulnerability, dependence, exposure, fragility, susceptibility and resilience. In Section 4, the concept of an infrastructure interdependency is described along with the implications for dealing with emerging areas of concern in the field of critical infrastructures; the section also illustrates how interdependencies can enable the anticipation of risk in interdependent infrastructures. Section 5 uses healthcare as a critical infrastructure system that must be managed as an interdependent system. Implications of interdependencies in healthcare are articulated with respect to risk assessment. Section 5 also describes an interdependency-induced risk approach for strategic healthcare planning. The paper concludes with implications for risk formulation for interdependent infrastructures. Also, future research related to measuring interdependencies and managing critical infrastructures as integrated systems of systems is discussed.

2. Critical infrastructures

Widespread usage of the term "critical infrastructure" gained traction in 1995 after the Oklahoma City bombing and the 1998 U.S. embassy bombings in East Africa. The notion of critical infrastructures also increased in importance as a result of the realization that information warfare could leverage the increasing dependence on information and computerized control systems [21]. This created a path for legislation aimed at protecting infrastructures and their users in the United States. The establishment of the President's Commission on Critical Infrastructure Protection (PCCIP) in 1996 was a major driver for critical infrastructure management [21,22].

In Europe, the European Council created the European Programme for Critical Infrastructure Protection (EPCIP) in 2004 to provide enhanced security for critical infrastructures in the European Union (EU). The goal of EPCIP is to "assure the continued functioning of Europe's critical infrastructure" [23]. While developing specific governance principles at the European level (i.e., European critical infrastructures) and the national level (i.e., national critical infrastructures), the European Council highlighted the effects of the trans-boundary nature of infrastructures in causing cascading events [24].

Research in the field of critical infrastructures is aimed at maintaining and sustaining public wellbeing. Thissen and Herder [18] suggest that "the functioning of modern society… depends on the quality of infrastructure facilities available… [and that]…over time infrastructures have become increasingly critical to the functioning of society, as economic and social processes to a large extent rely on the services provided by such systems". Moreover, societal changes continue to shape the meaning of infrastructure systems. For instance, "telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water supply systems, emergency services (including medical, police, fire, and rescue), and continuity of government" are critical infrastructures [25]. The 2003 Homeland Security Presidential Directive (HSPD-7) [26] identifies terrorism as a major focus and introduces the concepts of key resources, public morale and confidence as elements that can have a debilitating impact on society. Additionally, previously unidentified elements (e.g., chemical and hazardous materials, and postal and shipping industries) are now characterized as critical [26].

More recently, national monuments, icons, dams and critical manufacturing were identified as critical under Presidential Policy Directive 21 issued by the Obama Administration [27]. The broadening of the term critical infrastructures is also evident in the Patriot Act of 2002 when compared with the 1996 PCCIP, where the concern is restricted to "defense or economic security" [25]; notably, the Patriot Act includes "security, national economic security, national public health or safety, or any combination of those matters" [28]. Table 1 illustrates the different perspectives with regard to critical infrastructures.

This paper adopts the definition for critical infrastructure as given in [31]:

> "*…so vital and ubiquitous that their incapacity or destruction would not only affect the security and social welfare of any nation, but also cascade across borders.*"

The representative sample of literature was selected to illustrate that public health, economy, national security and