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Review

Review on modeling and simulation of interdependent critical infrastructure systems

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A R T I C L E I N F O

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A B S T R A C T

Modern societies are becoming increasingly dependent on critical infrastructure systems (CISs) to provide essential services that support economic prosperity, governance, and quality of life. These systems are not alone but interdependent at multiple levels to enhance their overall performance. However, recent worldwide events such as the 9/11 terrorist attack, Gulf Coast hurricanes, the Chile and Japanese earthquakes, and even heat waves have highlighted that interdependencies among CISs increase the potential for cascading failures and amplify the impact of both large and small scale initial failures into events of catastrophic proportions. To better understand CISs to support planning, maintenance and emergency decision making, modeling and simulation of interdependencies across CISs has recently become a key field of study. This paper reviews the studies in the field and broadly groups the existing modeling and simulation approaches into six types: empirical approaches, agent based approaches, system dynamics based approaches, economic theory based approaches, network based approaches, and others. Different studies for each type of the approaches are categorized and reviewed in terms of fundamental principles, such as research focus, modeling rationale, and the analysis method, while different types of approaches are further compared according to several criteria, such as the notion of resilience. Finally, this paper offers future research directions and identifies critical challenges in the field.

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1. Introduction

The economy of a nation and the well-being of its citizens depend on the continuous and reliable functioning of infrastructure systems. According to the report of the U.S. President′s Commission on Critical Infrastructure Protection (PCCIP) [164], an infrastructure system is defined as "a network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services". Among all infrastructure systems, those systems "whose incapacity or destruction would have a debilitating impact on the defense and economic security" are regarded as critical. Different countries have slightly different lists detailing their critical infrastructure systems (CISs), but most contain the following systems: telecommunications, electric power systems, natural gas and oil, banking and finance, transportation, water supply systems, government services, and emergency services.

CISs are not isolated but highly interconnected and mutually interdependent [172,157,174]. For example, water and telecommunication systems need steady supply of electric energy to maintain their normal operations while electric power systems require the provision of water and various telecommunication services for power generation and delivery. Interdependencies can improve infrastructure operational efficiency, but recent worldwide events such as the 1998 storm in Canada, the 2001 World Trade Center attack, the 2003 North American blackout, the 2004 hurricane season in Florida, the 2007 UK floods and the 2010 Chile and the 2011 Japan earthquakes have shown that interdependencies can increase system vulnerability. The damage in one CIS can produce cascading failures, sending ripple effects throughout regional or national scales. Also, most CISs are becoming more congested as population and demands grow, as in the case of the U.S. electric power system. Its increasing demands have not been met by the corresponding increase in capacity and the major blackouts (affecting 1 million or more people) occur about every 4 months on average in the United States [118]. This increased vulnerability of single CIS can be easily amplified due to the interdependencies. Hence, modeling and simulation of interdependent CISs become a critical field of contemporary research and study.

The governments in different countries also recognize the increasing importance of CISs and their interdependencies. In 1996, U.S. President Clinton established the President′s Commission on Critical Infrastructure Protection (PCCIP). This commission comprehensively reviewed and recommended many national policies for protecting CISs to assure their continued operations, with the final report released in October of 1997 [164]. In 1998, the Presidential Decision Directive (PDD) no. 63 was released. It set a national goal that the United States should achieve and maintain the ability to protect the nation′s CISs from deliberate attacks by 2003. Several institutions and departments have since been founded and expanded to protect CISs, including the National Infrastructure Protection Center (NIPC), the National Infrastructure Simulation and Analysis Center (NISAC), and the U.S. Department of Homeland Security (DHS). Similarly, other countries and regions have also made some efforts to better protect their CISs, such as the European Program on Critical Infrastructure Protection (EPCIP), the Critical Infrastructure Program for Modeling and Analysis in Australia, the National Critical Infrastructure Assurance Program in Canada, the Project of Dutch Approach on Critical Infrastructure Protection in the Netherlands, the Critical Infrastructure Resilience Program in the UK, and the Critical Infrastructure Protection Implementation Plan in Germany. This increased government attention has been followed by increases in funding to universities, national laboratories, and private companies involved in the modeling and simulation of CISs interdependencies, which have further led to much innovative and diverse work.

Existing studies on interdependent CISs can be classified in different ways. Some scholars have proposed different taxonomies and compared the studies in terms of different criteria. For example, Pederson et al. [156] summarized studies up to 2006 and compared their research using six criteria: infrastructures, modeling and simulation technique, integrated vs. coupled models, hardware/software requirements, intended user and maturity level. Eusgeld et al. [71] grouped modeling and simulation techniques up to 2008 into eight categories: agent-based modeling, system dynamics, hybrid system modeling, input–output model, hierarchical holographic modeling, the critical path method, high level architecture, and petri nets. Each category was evaluated according to nine criteria: maturity, paradigm, monitoring area, data needs, course of triggered events, types of events, types of interdependencies, design strategies, and modeling focus. Satumtira and Dueñas-Osorio [190] categorized the existing studies up to 2010 according to the following attributes: the mathematical method, modeling objective, scale of analysis, quality and quantity of input data, targeted discipline and end user type. Also, there are many other review references providing classifications of the modeling approaches as well as the evaluation criteria [86,37,165,169,191,82,215,20,21,56,158,196]. Specially, [87] provided a meta-review on 12 review references in the field and suggested a list of 11 categories of criteria and 25 sub-criteria for characterizing each type of models. However, all these review references only cover a small part of the existing studies and focus more on comparisons of the modeling rationale, without carefully reviewing their extensions and applications. Also, none of these papers review existing studies from an overarching perspective, such as the emerging notion of resilience, where resilience is a relatively new yet essential concept in infrastructure engineering and is regarded as the joint ability of infrastructure systems to resist (prevent and withstand) any possible hazards, absorb the initial damage, and recover to normal operation [148,149].

This paper provides a comprehensive review in the field and groups the modeling approaches into several broad types: empirical approaches, agent based approaches, system dynamics based approaches, economic theory based approaches, network based approaches, and other approaches. Different studies of each type of the approaches are grouped and reviewed in terms of key principles, such as research focus, modeling rationale, and the analysis method, while different types of approaches are further compared according to several criteria, such as resilience as the main perspective. The paper is organized as follows: Section 2 introduces the types of interdependencies and shows their evidence under some extreme events. Section 3 summarizes the conceptual and qualitative studies in the field, which pave the way to model and simulate CISs interdependencies. Section 4 critically reviews different modeling and simulation approaches, and then Section 5 provides the comparisons across different approaches, and identifies future research directions and challenges. Finally, Section 6 offers general conclusions and insights from the literature review.

2. Types and evidence of interdependencies

CISs are dependent and interdependent in multiple ways, where dependency refers to the unidirectional relationship and interdependency indicates the bidirectional interaction [172]. Usually, dependencies are regarded as interdependencies unless they are specially referred, which is also applied in this paper. To categorize CISs interdependencies, different scholars have provided different classifications, as summarized in Table 1.

In normal operation, some interdependencies are invisible, but under some disruptive scenarios, they emerge and become obvious. To show the evidence of interdependencies and their impacts, this