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Interconnectedness and interdependencies of critical infrastructures in the US economy: Implications for resilience

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HIGHLIGHTS

- A systems framework is developed to understand resilience of the US economy.
- Graph theory helps understand topological properties of the US EIO network.
- Hypothetical disruptions on CIS help determine economic interdependencies.
- Implications of interconnectedness and interdependencies on resilience are studied.
- US Economic network is vulnerable to greater CIS interdependencies.

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ABSTRACT

Natural disasters in 2011 yielded close to $55 billion in economic damages alone in the United States (US), which highlights the need to reduce impacts of such disasters or other deliberate attacks. The US Department of Homeland Security (DHS) identifies a list of 16 Critical Infrastructure Sectors (CIS) whose incapacity due to disruptions would have a debilitating impact on the nation's economy. The goal of this work is to understand the implications of interdependencies among CIS on the resilience of the US economic system as a whole. We develop a framework that combines the empirical economic input–output (EIO) model with graph theory based techniques for understanding interdependencies, interconnectedness and resilience in the US economic system. By representing the US economy as a network, we are able to analyze its topology by separately looking at its unweighted and weighted forms. Topological analysis of the US EIO network suggests that it exhibits small world properties for the unweighted case, and in the weighted case, the throughput of industry sectors follows a power-law with an exponential cutoff. Implications of these topological properties are discussed in the paper. We also simulate hypothetical disruptions on CIS in order to identify industrial sectors that experience the largest economic impacts, and to quantify systemic vulnerability in economic terms. In addition, insights from community detection and hypothetical disruption scenarios help assess vulnerability of individual industrial communities to disruptions on individual CIS. These methodologies also provide insights regarding the extent of coupling between each CIS in the US EIO network. Based on our analysis, we observe that excessive interconnectedness and interdependencies of CIS results in high systemic vulnerability. This information can guide policymakers to design policies that improve resilience of economic networks, and evaluate policies that might indirectly increase coupling between CIS.

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1. Introduction

Modern society is critically dependent on the stability and performance of complex infrastructure networks for almost every social and economic function. Infrastructure assets, systems and networks that provide essential services and form the nation's backbone are referred to as critical infrastructure sectors (CIS). The US Department of Homeland Security (DHS) identifies a list of 16 CIS whose incapacity due to hazards, ranging from natural disasters to cyber attacks, would have a debilitating impact on the nation's security, economy, health and safety [1]. The far-reaching importance of CIS is a result of increasing interconnectedness between them (as is the case with energy supply, telecommunications and transportation), which may result in unpredictable consequences and risks. Additionally, individual industry sectors in an economic system are inherently interdependent and interconnected, and disruption on any single sector can trigger a ripple throughout the economy affecting sectors that are directly and indirectly interacting with the triggering sector [2].

In recent times, impacts arising from natural disasters like Hurricanes Katrina and Sandy, infrastructure failures like the Northeast blackout, epidemics like the H1N1 influenza, terrorist attacks like the 9/11, and social unrests like the Arab Spring have had large consequences across national and international boundaries [3–5]. Impacts from these events have been significantly amplified because of the interdependencies and feedback mechanisms between our society, the environment and the CIS [6]. According to a National Research Council report, natural disasters affecting the US in 2011 alone yielded close to $55 billion in economic damages [7]. The historical data on economic impacts of natural disasters worldwide exhibits an upward trend, suggesting that this number will continue to soar [8]. Cascading impacts arising from increasing number of natural, man-made and technological disasters may continue to rise as complexity grows. There is an urgent need to identify, understand and analyze functional interdependencies and structural vulnerabilities in economic systems [4,9–12].

The recent US Presidential Policy Directive (PPD 21) on *Critical Infrastructure Security and Resilience* recommends steps to manage risk and strengthen the security and resilience of CIS [13]. While the definition for resilience may vary across disciplines and systems, the PPD defines CIS resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions". This report highlights the importance of building resilient CIS for improving the overall resilience of the economic system.

Economies are self-organizing, complex systems comprised of industrial sectors, firms, and consumers that interact with and react to one another [14]. Resilience for economic systems has been previously defined in terms of its structural robustness as the ability to maintain its functionality in response to disruptions [15,16]. Based on this definition, key sectors/hubs for the economic system are identified that are a source of vulnerability to comment on its resilience. However, previous studies stop short of assessing the subsequent cascading impacts on rest of the sectors resulting from a disruption on one of these key sectors. To address this issue, we adapt the concept of ecological resilience to define resilience of complex industrial and infrastructure systems as their ability to resist structural and functional change, and minimize deviation from its original state during initial decline after disruption [17–19]. As per this definition, an economic system is not considered resilient if it suffers large cascading impacts because of its topology, which is governed by the patterns of interconnectedness and interdependencies between industrial sectors.

Previous work has focused on the challenging task of characterizing, modeling, and simulating interconnectedness and interdependencies of complex CIS. Zimmerman categorizes infrastructure interdependencies as *functional* or *spatial* [20]. *Functional interdependencies* are those in which infrastructure systems are dependent on one another for their operation (e.g. the functioning of the railroad system is dependent on communication systems). *Spatial interdependencies* occur due to geographic proximity of infrastructures (e.g. underground collocated lines of telecommunication, power, water, and sewage infrastructures can affect one another). While modeling spatial interdependencies between various CIS is equally essential, such a study must be done at a regional level with high-resolution data. We restrict our focus on understanding and quantifying functional interdependencies between CIS and other industry sectors.

Previous work has focused on utilizing empirical approaches based on data from incident records (media reports, newspapers, official ex post assessment, etc.) to quantify CIS interdependencies [21–29]. Other modeling and simulation techniques such as agent based modeling (ABM) and system dynamics (SD) have also been employed to model interdependencies and complex adaptive behavior of CIS [30]. Some tools based on ABM and SD models include Aspen, Aspen-EE, CommAspen, and N-ABLE developed by Sandia National Laboratories [31–37]. While the above-mentioned methodologies are valuable, their application is restrictive because lack of CIS-related data hampers calibration of model parameters and functions, and inhibits validation of results [38].

An attractive and alternative method for modeling CIS interdependencies is via the use of Economic Input–Output (EIO) model, originally developed by Nobel laureate Wassily Leontief. Unlike other methodologies the EIO model is based on comprehensive empirical data published by national and international agencies such as Bureau of Economic Analysis (BEA) in the US and Organization for Economic Co-operation and Development (OECD) globally. The EIO model divides the economy of a particular region into industries or sectors and tracks the monetary transactions between them. It is a static and linear model of all purchases and sales between economic sectors for a specific time period based on the technological recipe of production. EIO models are useful for modeling short-term cascading impacts caused by perturbations on the interconnected industry sectors, and identifying functional interdependencies between them [39–42].

At the core of an EIO model is the transaction table also known as the flow or transaction matrix (Z) that accounts for all payments to and from a sector in any given year (shown in Table 1). It is represented as z_{ij} where sector j pays sector i the monetary value of the goods and services provided by sector i to sector j. In addition to the inter-industry transactions,