An Input-Output Model to Determine the Operability and Economic Impacts of IT on Interdependent Industries

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Abstract— **Disasters, such as hurricanes and terrorist attacks, are damaging to various critical infrastructure systems. They disrupt supply chains and have adverse effects on the productivity of economic sectors. The IT sector is a highly vulnerable and critical infrastructure in the United States. This sector is susceptible to various forms of malicious attacks. Previous publications focus on security shortfalls existing within the IT system architecture and organizational policy. This paper asserts the need for a broader exploration of IT security as a macroeconomic system engineering problem. In this paper, we conducted a study to evaluate the inoperability impact and economic losses experienced by various industries due to a direct attack on the IT sector.**

Keywords: **disaster; risk; sector analysis; economic input-output model**

I. Introduction

In the fall of 2012, Hurricane Sandy, or Superstorm Sandy, battered most mid-Atlantic region states. This hurricane marked the first unscheduled closure of the stock market since the 9/11 terrorist attacks. The economic loss experienced by the storm was roughly $20 billion in property damage and $60 billion considering lost work time, tax revenue on wages, and reduced commerce during business closures [1].

Between October 2019 and December 2020, the SolarWinds Hack went undetected within the federal government. This attack, likely perpetrated by a Russian intelligence agency, exposed fundamental cybersecurity vulnerabilities within the government and private sector [2]. Malware was installed in the networks of around eighteen thousand companies and government organizations. The estimated costs to contain and fix damages associated with this attack is nearly $100 billion [2].

In May 2021, Colonial Pipeline, an American oil pipeline system-originating in Houston, Texas-suffered a ransomware cyber-attack [3]. This attack impacted the computerized equipment managing the pipeline. Overseen by the FBI, the company paid the hacker group 75 bitcoin, in today's market $3.44 million [3]. Approximately 100 gigabytes of data were stolen the day before the attack [3].

A. Problem Statement

As advancements in technology are made, direct and indirect threats to critical infrastructure increases. Disasters have been subject to research and a source of concern for academia, government, and independent agencies [4]. As seen above the United States has experienced significant loss due to natural and man-made disasters over the past decade. Prior research has explored shortfalls within policy and infrastructure. This research studies the operability and economic interdependencies that exist within the sectors that make up the United States gross domestic product (GDP). This occurs through measuring the relationships between sectors, specifically those related to IT and the remaining sectors. The following questions will be explored:

(i) Given an attack what would be the direct economic impact on the IT sector?
(ii) Given a disruption to the IT sector, what sectors are most critically affected in terms of reduced reliability and economic loss?
(iii) How significant are the variations in economic loss and inoperability from year to year due to IT sector disruptions?

In this paper, reduced reliability is quantified using the inoperability measure, and economic loss is the monetary value associated with the sector's inoperability. The applied methodology will be an inoperability input-output model (IIM) utilizing 5 years of data collected by the Bureau of Economic Analysis (BEA). Results will include impact analysis of the disruptions to each sector caused by a direct attack to the IT infrastructure. Each sector will be ranked based on the resulting inoperability and economic loss. The ranking scale will be established based on greatest to least inoperability and economic loss experienced. The research will discover and seek to explain any year-to-year ranking variations to the sectors. The results will provide insight aiding in policy development and resource allocation to the sectors deemed most critically affected based on inoperability and economic loss.

B. Paper Organization

The subsequent sections will address the following: a literature review of disaster risk assessments and the application of input/output models towards macroeconomics; the application of the input/output methodology, definition of key variables, and the approach applied to data collection; the results of the applied methodology; and the potential for future research into the identified issues.

C. Scope and Limitations

This paper evaluates interdependency between the IT-sector and the various industries which account for the GDP. The sole focus is threat to monetary and functionality of other industries should a disaster to IT-sector occur. It does not evaluate specific sector policies, physical system interdependency, and investments or applications made towards resilience to threats.

II. Literature Review

A. Disaster Risk Assessment

A risk assessment is the process of identifying hazards and analyzing potential outcomes if the hazard occurs [5]. There are many assets at risk due to hazards. Assets include people, buildings, information technology, utility systems, raw materials and finished goods [5]. As risk assessments are performed, weaknesses should be identified which cause an asset to be susceptible to damage.

B. Input-Output Model

The input-output model is analytical framework developed by Professor Wassily Leontief in the late 1930s [6]. This method is utilized to study and analyze the economic equilibrium in various fields such as energy, environment, and risk analysis [7]. The development of this model was a significant achievement for explaining how production outputs of interdependent sectors are applied as intermediate inputs to other inputs or as final demand [8].

C. Inoperability Input/Output Model (IIM)

The Inoperability Input-Output Model (IIM) is based on Leontief's input-output model [9]. This model characterizes interdependencies amongst sectors in the economy and analyzes initial disruptions to a set of sectors and the resulting ripple effects [9].

Traditional I-O models have been applied to problems of economic analysis. For over a decade, I-O applications have been applied to disaster risk analysis. The model was initially transformed into an inoperability I-O model by Haimes and Jiang [10]. In 2004, it was again evolved by Santos and Haimes [10]. Inoperability is the lack functionality by an economic sector to maintain its expected performance due to an internal or external disruption. In addition to inoperability, this I-O model can be applied to the analysis and distribution of economic loss [10]. This evaluation can be conducted on sectors both directly and indirectly effected [10]. IIM can be applied to various real-world scenarios modeling rippled distributions to interdependent sectors. A multi-objective approach using economic loss and inoperability metrics can be used to identify critical sectors that are affected the most by the disruptive event [10].

Dietzenbacher & Miller [11], argue the relevancy and straightforwardness to the application of IIM. The authors state that this technique has been used to create much interesting work in disaster analysis. For example, Haimes et al., uses IIM to model impacts of willful attacks on interdependent sectors. High altitude electromagnetic pulse (HEMP) is an intense electromagnetic blast induced by a nuclear explosion at a high altitude [12]. Various results were found to include direct economic and power-production impact on power supply and generation sectors. Additionally, production and economic impacts caused by psychological factors induced by a HEMP attack.

Critics, such as Oosterhaven [13], present the case that the focus of IIM is only part of the negative indirect economic impacts as a disaster. They present the case that IIM neglects most of the positive direct impacts. The belief is it is not properly suited to prioritize industry policy intervention aiming to reduce the negative impact of a disaster [13].

D. IIM in Macroeconomics

Due to China's rapid growing economy, the country is consuming a robust number of resources. Unfortunately, the rapid growth has resulted in significant environmental issues. "Water-Energy-Carbon Emissions nexus analysis of China: An environmental input-output model-based approach," by Wang et al. [14], used an environmental input-output model created to assess water, energy, and carbon emission coefficients. The findings were that the Water-Energy-Carbon Emissions nexus characteristics of light industry, heavy industry, and service industry were similar: water-intensive, energy-intensive, and carbon-emission-intensive.

Agriculture consumed 64.38% of the national water supply; however, the water utilization efficiency was only 32% [14]. Agriculture had much higher water consumption and direct water consumption coefficients. Light industry, service industry, and heavy industry were the top three sectors in terms of indirect water consumption coefficients. Finally, heavy industry, light industry, and service industry were the top three sectors with the highest indirect energy consumption coefficients and carbon emission coefficients. The consumption (water and energy) and CO_2 emission coefficients can provide significant support for sustainable development strategies [14].

III. Methodology

Described in this section will be the methodology applied to expand the capabilities of IIM for assessing loss due to IT- sector inoperability. The methodology includes the process for which we structure the initial disruption to IT-sector, which then is applied to all interdependent sectors as direct inoperability inputs.

A. IIM Framework

This study will utilize the Inoperability Input-Output Model (IIM) defined by the following:

$$x = Ax + c$$

Defining variables:

- x – Output vector (Economic Loss)
- Ax – Intermediate (Value of Sector)
- c – Final Demand (inoperability)

This formula states that the total production output (x) is comprised of intermediate transactions (Ax) and final demands (c). The I-O data is formulated from a technical coefficient matrix obtained from the Bureau of Economic Analysis (BEA).

B. Data Collection

The primary source will be secondary data collected from the Bureau of Economic Analysis (BEA). BEA economists produce closely assessed statistics, including the gross domestic product (GDP) for the United States. Their mission includes promoting a better understanding of the U.S. economy by providing timely, relevant, and accurate economic accounts [15].

The economists who generate and publish the BEA data have made contributions to research in various industries. Oldenski [16], uses firm-level data on U.S. multinationals to show how offshoring effects domestic employment. Grimm [17] builds on the international statistical community's progress toward more precisely defining the types of services that fall into information and communications technology (ICT).

C. Data Transformation

A data transformation will be conducted through aggregation of the industry sector data from the U.S. Department of Commerce Bureau of Economic Analysis (BEA) matrix to develop the I-O matrix reflecting the new IT sector. The IT sector will be defined by the following industries:

- Broadcasting and telecommunications
- Data processing, internet publishing, and other information services
- Computer systems design and related services

D. Scenario Structuring

A 0.1, 10%, level of inoperability will be applied to the IT Sector. This will occur through assessing the initial perturbation to the IT sector and modeling the propagation dynamics to IT-dependent sectors. The modeling approach will be an extension of the IIM using a single-event model to simulate an IT disruption and the indirect effect on interdependent economic systems.

IV. Results and Findings

This case study analyzes a simulation of a 10% disruption to operability to the defined IT sector. The following address the results of the direct and indirect impact caused by the disruption. Tables and figures will be used to provide a visual display.

A. Direct Impacts

This study analyzes a 5-year period in which a 10% disruption to operability of the IT sector contributes to the direct economic loss within the IT sector. The following table will display the economic loss to the IT sector if a 10% disruption were to occur.

Table I
IT-sector Economic Loss (2016-2020)

Year	Economic Loss (Million $)
2016	172,784.68
2017	173,468.73
2018	196,594.22
2019	205,404.33
2020	216,852.16

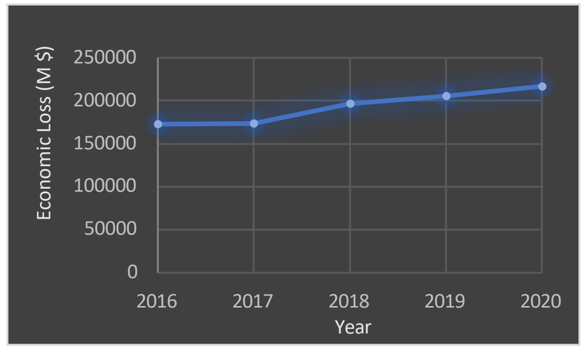

Fig. 1: 2016-2020 Expected IT-sector Economic Loss

As shown in the Table 1 and Figure 1 above, between 2016-2020, the economic loss that would be experienced by the IT-sector during this time period displays a slight increase. The average economic loss during this period is 193,020.82 (in million $). The most drastic change is experienced between 2017 and 2018. This result is most shocking considering the reliability of IT related systems during the beginning of the pandemic.

B. Indirect Impact (Operability)

Indirect inoperability is the level of diminished operability to which a specific sector would become if the IT sector was to become inoperability by 10%. The figures below project the top 10 sectors most significantly impact operability would be greatest affected and the level of inoperability they would experience between 2016-2020.

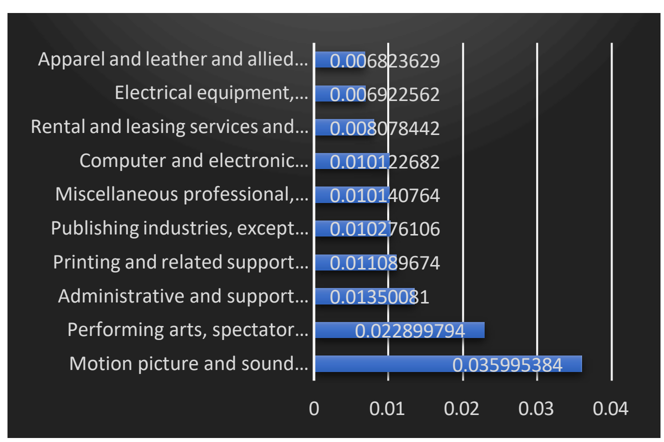

Fig. 2: 2016 Top 10 Ranked Indirect Inoperability

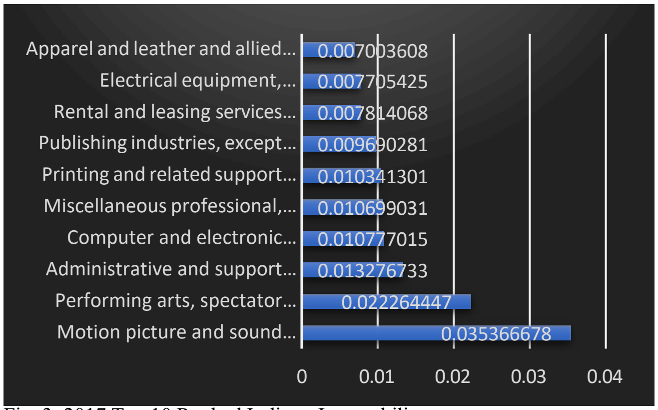

Fig. 3: 2017 Top 10 Ranked Indirect Inoperability

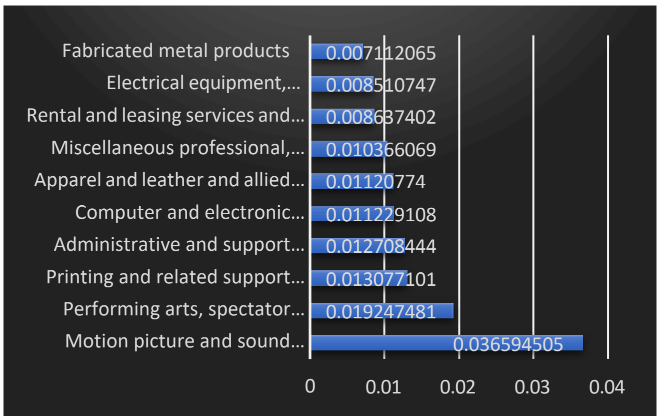

Fig: 4: 2018 Top 10 Ranked Indirect Inoperability

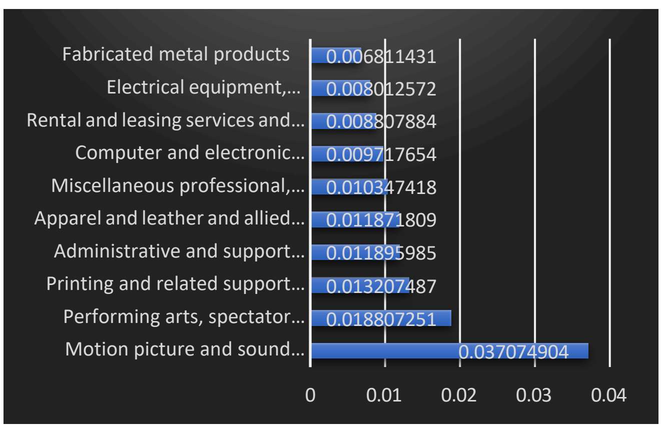

Fig. 5: 2019 Top 10 Ranked Indirect Inoperability

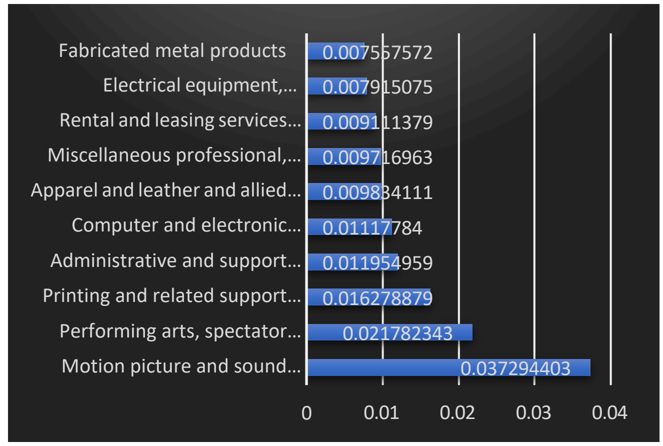

Fig. 6: 2020 Top 10 Ranked Indirect Inoperability

Between 2016-2020, the sector that would experience the largest degree of inoperability loss is motion picture and sound recording industries. The estimated degree of inoperability ranges between 3.65-3.7%. The remaining sectors all were consistently present within the top 10 having slight rank variations.

C. Indirect Impact (Economic Loss)

The indirect economic loss over the 5-year period, 2016-2020, is evaluated to determine which sectors would be most impacted by a 10% IT-sector inoperability level. The figures below display the Top 10 sectors and the loss they are expected to incur.

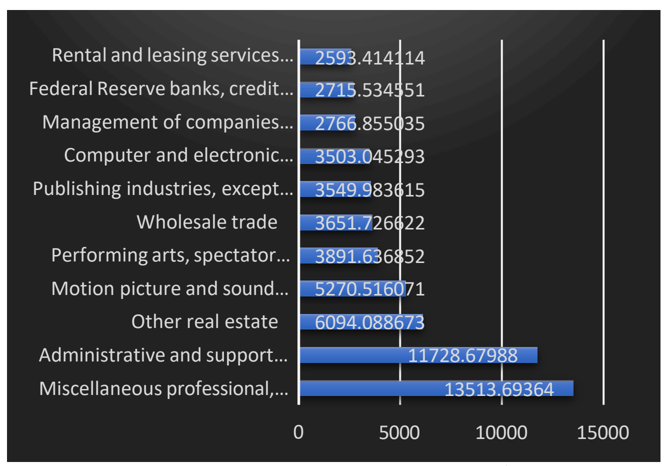

Fig. 7: 2016 Top 10 Ranked Indirect Economic Loss (Mil $)

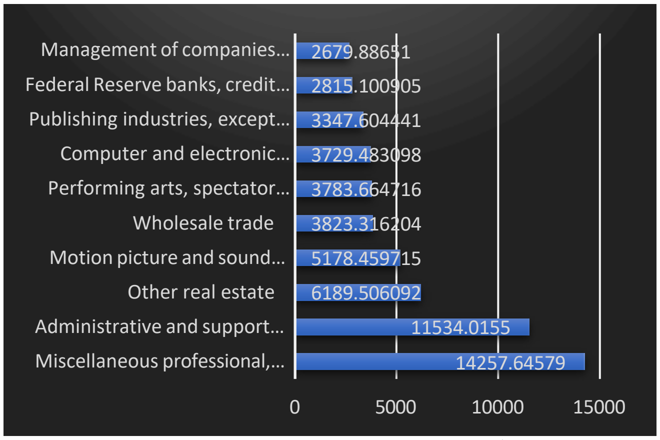

Fig. 8: 2017 Top 10 Ranked Indirect Economic Loss (Mil $)

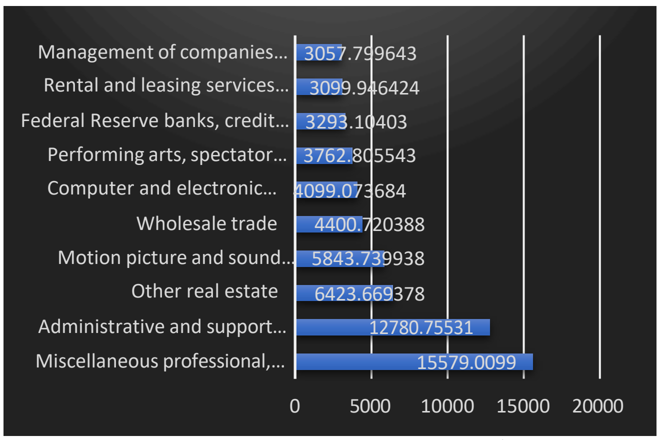

Fig. 9: 2018 Top 10 Ranked Indirect Economic Loss (Mil $)

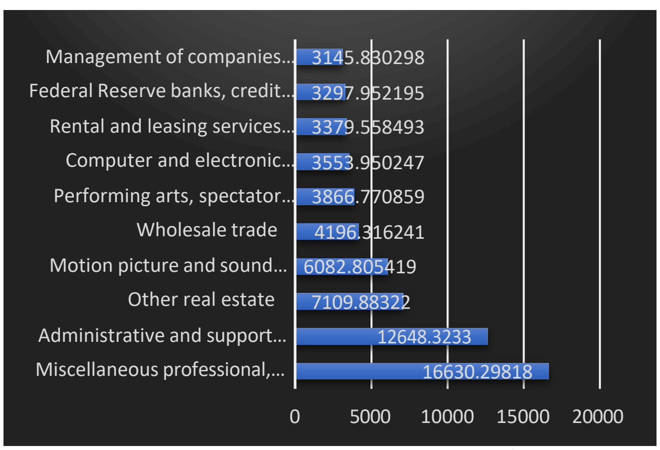

Fig. 10: 2019 Top 10 Ranked Indirect Economic Loss (Mil $)

Between 2016-2020, the sector that would experience the sector which showed consistently the most economic loss is Miscellaneous professional, scientific, and technical service. In 2020, this sector dropped to the 34th rank out of the 67 that were evaluated against an inoperability of 10% to the IT-sector. The changes experienced in 2020 can be explained by the reaction to the COVID pandemic. Of the 10 sectors consistently, 3 remained in the Top 10 in 2020. Those sectors are as follows: Administrative and support services, Motion picture and sound recording, and Computer and electronic products.

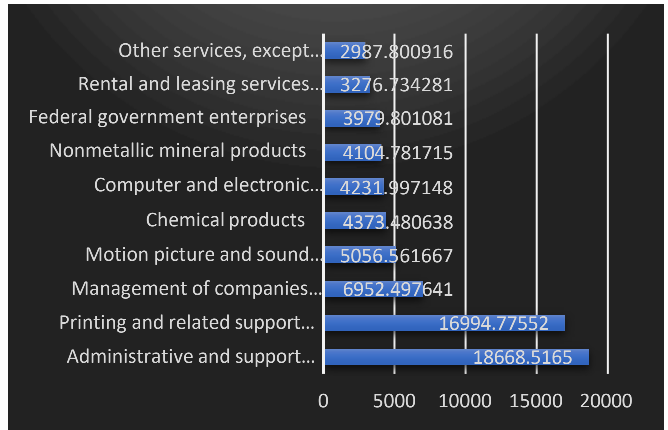

Fig. 11: 2020 Top 10 Ranked Indirect Economic Loss (Mil $)

D. Other Significant Results

Based on the analysis, inoperability and economic loss can vary. A firm ranked low, within the top 10, on inoperability may not have the equivalent in economic loss. Averaging the 5-year time span, 2016-2020, six of the ten sectors ranked in the top ten for both inoperability and economic loss. No sector within the Top 10 ranks the same for both inoperability and economic loss. Based on this analysis, it has been found that a firm may have a higher degree of inoperability but experience less economic loss. This relationship can be explained by the level of generated revenue. Industries with a high profitability may be impacted less by inoperability to an interdependent industry, IT sector. The tables below provide a comparison between the rankings of inoperability and economic loss:

Table II
Rank Comparison (Inoperability)

Sector	Inoperability	Economic Loss
Motion picture and sound recording industries	1	4
Performing arts, spectator sports, museums, and related activities	2	6
Administrative and support services	3	2
Printing and related support activities	4	25
Computer and electronic products	5	7
Miscellaneous professional, scientific, and technical services	6	1
Apparel and leather and allied products	7	47
Rental and leasing services and lessors of intangible assets	8	10
Electrical equipment, appliances, and components	9	26
Fabricated metal products	10	11

Table III
Rank Comparison (Economic Loss)

Sector	Economic Loss	Inoperability
Miscellaneous professional, scientific, and technical services	1	6
Administrative and support services	2	3
Other real estate	3	16
Motion picture and sound recording industries	4	1
Wholesale trade	5	35
Performing arts, spectator sports, museums, and related activities	6	2
Computer and electronic products	7	5
Federal Reserve banks, credit intermediation, and related activities	8	27
Management of companies and enterprises	9	20
Rental and leasing services and lessors of intangible assets	10	8

V. Conclusion

In present society, as technology advances are made there is an ever-growing threat to all aspects of society. Disasters within the IT sector, whether man-made or natural, pose a great threat to the United States economy. As seen in Hurricane Sandy, SolarWinds and Colonial Pipeline Hack disasters are costly events and can potentially take decades to recover from. This research identified the interdependence amongst the IT-sector and other sectors that make up the U.S. GDP.

The research provides the framework to evaluate the impact that a disaster, whether man-made or natural, to the IT-sector would pose on the interdependent sectors that make up the United States economy. We developed an IIM to accommodate the use of customizable inoperability inputs within the IT sector to simulate the economic loss within the sector. Additionally, we simulated the indirect effect, inoperability and economic loss, to other sectors that make up the U.S. economy. The applied model evaluated inoperability and economic loss behaviors over a 5-year span (2016-2020).

We determined what the projected economic loss would be experienced by the IT-sector if it were to become 10% inoperable. Next, we identified the top 10 sectors with the greatest risk for inoperability and economic loss. Finally, we found that a higher level of inoperability does not necessarily correlate to a high economic loss. It has been determined that disruptions to the IT-sector pose significant threat to the interdependent sectors. Methods to reduce ripple impacts caused by inoperability and economic loss should be explored.

This model can be replicated for use in various other countries such as Australia, Japan, European, and others that have established I-O accounts. Additionally, the model can be applied to evaluate regional IT-sector disasters within the United States utilizing BEA's RIMS.

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