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Demand-Reduction Input-Output (I-O) Analysis for Modeling Interconnectedness

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Abstract

The paper discusses the *demand-reduction I-O inoperability model* to analyze the economic impact of demand reductions on a system of interconnected infrastructures. The propagation of inoperability depends upon the degree of interdependency of one infrastructure on another. A case study comprising twelve critical interconnected infrastructure sectors is presented. The interdependency matrix for this case study is derived via a transformation of the national industry-by-industry transactions data as published by the Bureau of Economic Analysis. The paper highlights the use of *geographical* and *functional* decompositions to tailor the demand-reduction analysis to specific US regions, or to components of a large-scale infrastructure, respectively.

Introduction

Inoperability analysis in this paper connotes a process of studying how risks can propagate and proliferate through a system of interconnected infrastructures. *Perturbations* in the form of natural disasters, accidents, or willful attacks can set off a chain of cascading impacts, and thus risks, on interconnected infrastructures. A technical paper by the University of Virginia's Center for Risk Management of Engineering Systems (UVA-CRMES) asserts that the higher degrees of interdependencies exhibited by our critical infrastructures to date—due in part to their increasing reliance on modern technology—make them more vulnerable to willful attacks [UVA-CRMES 2002]. The September 11, 2001 attacks, for example, have

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demonstrated the strong interdependence and interconnectedness in various infrastructures and sectors of the United States.

Input-output (I-O) analysis was developed by Leontief in the 1930s to present a framework for addressing the interconnectedness among various sectors of the economy [Leontief 1951a and b, 1966]. Utilizing this framework, Haimes and Jiang [2001] developed the Leontief-based I-O inoperability model to describe how the impact of perturbations can cascade through a system of interconnected infrastructures. In this model, the term *inoperability* connotes the level of the system's dysfunction, expressed as a percentage of the system's nominal level of operation. Furthermore, inoperability is interpreted as the degradation of a system's capacity (or supply) to deliver its intended output due to the physical impact of such perturbations. Thus, we refer to the Haimes and Jiang I-O inoperability model as either *physical-based* or *supply-based.*

Through the *demand-reduction inoperability I-O model* (or *demand-based model*, for brevity), the paper aims to complement and supplement the already-developed physical-based model. While the physical-based model quantifies inoperability in terms of degraded capacity to deliver the intended outputs, the demand-based model addresses the demand reductions that can potentially stem from perturbations. Logically, the demand reduction of a perturbed industry further renders adverse impacts on the operation of other dependent industries.

The remainder of the paper is organized as follows: Section 2 highlights the literature sources relevant to the usage of I-O analysis. Section 3 discusses the demand-based model and demonstrates it via a case study comprising 12 national critical interconnected infrastructures. Sections 4 and 5 provide an array of methods to further enhance the demand-based model. Specifically, these methods include geographical decomposition (Section 4), and functional decomposition (Section 5). Finally, the Section 6 epilogue highlights how the demand-based model is integrated into a higher-level I-O framework via the temporal modeling of inoperability.

Input-Output Models

I-O analysis is concerned with modeling interdependencies among a system of interconnected entities. These entities can be characterized in terms of industries—as described by the Leontief economic I-O model—or of critical infrastructures—as described by the physical-based inoperability I-O model.

Leontief economic I-O model. The I-O analysis was formally introduced by Wassily Leontief in the 1930s to present a framework for the study of economic equilibrium. Through the use of I-O tables, the model is capable of addressing the interconnectedness among various sectors of the economy [Horton 1995]. Leontief was awarded the 1973 Nobel Laureate in Economics for his seminal work on the development of the I-O method and for its application to important economic problems. Miller and Blair [1985] provide a comprehensive introduction to the model and its applications. Leontief's I-O model describes the equilibrium and dynamic behavior of both regional and national economies. Thus, it is a useful tool in economic decisionmaking processes used in many countries [Peterson 1991]. Recent frontiers in I-O analysis were compiled by Lahr and Dietzenbacher [2001].

The US Department of Commerce [1998] maintains various types of economic tables (or matrices) through its Bureau of Economic Analysis (BEA) division. The BEA is responsible for documenting the transactions among various industries in the US economy. The detailed national I-O accounts are composed of nearly 500 industries, organized according to the Standard Industry Classification (SIC) codes. For brevity, we focus only on describing the make (**V**) and use (**U**) matrices. The *make* matrix would show the dollar values of the different column commodities *produced* by the different row industries. The *use* matrix, on the other hand, would show the dollar values of the different row commodities *consumed* by the different column industries. The BEA data do not directly specify the I-O matrix representing the industry-by-industry transactions. This matrix, which is called the *industry-by-industry technical coefficient matrix* in Leontief parlance, shows the proportion of the i^{th} industry's total output which serves as the input to the j^{th} industry's production. To derive the industry-by-industry technical coefficient matrix, we first need to normalize the use and make matrices with respect to the total commodity output (**y**) and total industry output (**x**) vectors, respectively. The described operations will yield the normalized make (**D**) and the normalized use (**B**) matrices.

$$d_{ij} = \frac{v_{ij}}{y_j} \Leftrightarrow \mathbf{D} = \mathbf{V}[diag(\mathbf{y})]^{-1} \qquad (1)$$

$$b_{ij} = \frac{u_{ij}}{x_j} \Leftrightarrow \mathbf{B} = \mathbf{U}[diag(\mathbf{x})]^{-1} \qquad (2)$$

The operator $diag(\boldsymbol{\theta})$ in (1), (2), and later equations represents the resulting diagonal matrix constructed from a given vector $\boldsymbol{\theta}$, i.e.,

$$diag(\boldsymbol{\theta}) = diag\begin{bmatrix}\theta_1\\ \theta_2\\ \vdots\\ \theta_n\end{bmatrix} = \begin{bmatrix}\theta_1 & 0 & \cdots & 0\\ 0 & \theta_2 & \ddots & \vdots\\ \vdots & \ddots & \ddots & 0\\ 0 & \cdots & 0 & \theta_n\end{bmatrix} \qquad (3)$$

We use the notation **A** to refer to the industry-by-industry technical coefficient matrix. Miller and Blair [1985] provide the derivation for **A** to be the product of the normalized make and the normalized use matrices.

$$a_{ij} = \sum_k d_{ik} b_{kj} \Leftrightarrow \mathbf{A} = \mathbf{DB} \qquad (4)$$

Defining **c** as the final demand vector for the industries, then the Leontief balance equation containing the industry-by-industry technical coefficient matrix (**A**) and the total industry output vector (**x**) is written as follows:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{c} \tag{5}$$

Physical-based inoperability input-output model. Modern infrastructures to date generally manifest higher degrees of complexity and interconnectedness, due largely to their increasing reliance on information technology [Longstaff et al. 2000; Longstaff and Haimes 2002]. Thus, it is likely that the vulnerability of a given infrastructure could pose additional risks to other dependent infrastructures [Haimes 2002]. A first-generation physical-based inoperability I-O model (or physical-based model, for simplicity) was developed by Haimes and Jiang [2001] to describe how the impact of terrorist attacks can cascade through a system of interconnected infrastructures. Inoperability connotes degradation in the system's functionality (expressed as a percentage relative to the intended state of the system). The mathematical formulation of the physical-based model is as follows:

$$\mathbf{x} = \mathbf{A}\mathbf{x} + \mathbf{c} \tag{6}$$

However, note that the interpretation of the model parameters in (6) is fundamentally different from the Leontief model in (5). The "supply" and "demand" concepts in the Leontief economy model now assume different interpretations and have been inverted to some extent in the physical-based inoperability I-O model. Although the mathematical construct of the two models is similar, in Leontief's model, **x** and **c** represent commodities typically measured in dollar units. In the physical-based model, the vector **c** represents the *input* to the interconnected infrastructures—perturbations in the form of natural events, accidents, or willful attacks. The *output* is defined as the resulting vector **x** of inoperability of the different infrastructures, due to their connections to the perturbed infrastructure and to one another. The long-run inoperabilities of the interconnected infrastructures following an attack can be calculated using (6) provided that **A** is stable.

The inoperability vector (**x**) describes the degree of functionality of interconnected infrastructures. Thus, it takes on values between 0 and 1, where flawless operation corresponds to $\mathbf{x} = 0$ or $x_1 = x_2 = \cdots = x_n$. When this condition is in effect, the infrastructures are said to be at their *nominal* or *ground state*. A perturbation input **c** will cause a departure from the ground state. It can intuitively set off a chain of effects leading to higher-order inoperabilities—coined as *cascading effects* by Rinaldi [1997]. For example, a power infrastructure (the k^{th} infrastructure) would initially lose 10% of its functionality due to an attack that delivers a perturbation (c_k) of 0.1. This defines the perturbation as the inoperability of the power infrastructure *right after* an attack. In addition, this inoperability propagated onto other power-dependent infrastructures will in turn cause other inoperabilities and ultimately perhaps additional inoperability in the power infrastructure itself. In general, we expect the long-run inoperability of an attacked infrastructure to increase from its post-attack value (i.e., the perturbation).

Demand-Reduction Inoperability Input-Output Model

Continued exploration of the prior work on I-O modeling (i.e., the physical-based model) indicates that no single model is capable of capturing the multiple visions, perspectives, or dimensions of a system. This philosophy is the basis for hierarchical holographic modeling (HHM)—a modeling schema for identifying and structuring multiple risk scenarios triggered by deviations from the system's "as planned" scenario [Haimes 1981, 1998; Kaplan et al. 2001]. Thus, while the already-developed physical-based inoperability I-O model analyzes the physical losses caused by natural and human-caused catastrophic events, it is necessary to consider other factors as well. Psychological factors, for one, have been shown to mirror the physical destruction delivered by such events. A comprehensive survey of the psychological effects of various types of disasters is documented by Norris et al. [2002]. Empirical studies such as those conducted by Susser et al. [2002] and Galea et al. [2002] specifically show the significance of the "fear factor" induced by the September 11, 2001 terrorist attacks. These papers suggest that fear can cause the public to reduce its demand for the goods/services produced by an attacked entity. Public apprehension of the safety of air transportation post 9/11, for example, caused a drastic reduction in the operations of airlines and of airline-dependent industries. Such retrenchments and changes in demand can have compelling economic repercussions (e.g., degraded production capacity) which add to the physical losses. The *demand-reduction inoperability I-O model* will be used to analyze the long-run adverse effects of demand degradation on the nominal operation levels of interdependent industries.

Model description. Central to demand-reduction inoperability I-O modeling is the analysis of how demand reduction can propagate from the directly attacked industry to others. As with the case of the physical-based model, the propagation of demand-based inoperability depends on an interdependency matrix—a matrix which describes the degree of coupling between infrastructures. By deriving the relationship between the demand-based I-O inoperability model and the original Leontief economic model, we establish a process of generating the interdependency matrix based on available economic data. The correspondence between these two models is given in UVA-CRMES [2002]:

$$\mathbf{q} = \mathbf{A}^{*}\mathbf{q} + \mathbf{c}^{*} \tag{7}$$

where the variables are defined as follows:

- $\mathbf{c}^{*}$ is the vector of normalized degraded demand (i.e., nominal demand minus post-attack demand, divided by the nominal production);
- $\mathbf{A}^{*}$ is the interdependency matrix, whose elements are derived from the industry-by-industry technical coefficient matrix ($\mathbf{A}$); and
- $\mathbf{q}$ is the vector of normalized production loss whose elements represent the ratio of unrealized production (i.e., nominal production minus post-attack production, divided by nominal production).

The normalized production loss (**q**) in the model is triggered by a terrorist-induced normalized degraded demand ($\mathbf{c}^*$). We also refer to **q** as the *demand-based inoperability*. The interdependency matrix ($\mathbf{A}^*$) in the demand-based I-O inoperability model can be generated based on a published industry-by-industry technical coefficient matrix. Thus, the demand-based I-O inoperability model can utilize the vast database available in the reports of the BEA. Through a transformation of the economic data collected and published by the agency, a sample demonstration of the demand-reduction inoperability I-O model is presented in the following section.

Sample implementation of the demand-reduction inoperability I-O model. The following example consists of the 12 representative industry sectors enumerated in Table 1. The data are obtained from US national I-O accounts released by the BEA [US Department of Commerce 1998]. These accounts contain the total industry outputs, denoted by the vector $\hat{\mathbf{x}}$ in Table 2. Using BEA's *Make* and *Use* tables, the resulting industry-by-industry technical coefficient matrix (**A**) for the twelve industry sectors is presented in Table 3.

Table 1. Industry sectors selected for the model.

Index	SIC[†] Code	Description
1	7.0000	Coal
2	31.0101	Petroleum refining
3	65.0100	Railroads and related services
4	65.0301	Trucking and couriers
5	65.0400	Water transportation
6	65.0500	Air transportation
7	66.0100	Telephone and telegraph, communication services
8	68.0100	Electric services
9	68.0301	Water supply and sewerage systems
10	70.0100	Banking
11	72.0101	Hotels
12	74.0000	Eating and drinking places

[†]Standard Industry Classification

Table 2. Total industry outputs ($\hat{\mathbf{x}}$), in million $.

Industry	*j=1*	*j=2*	*j=3*	*j=4*	*j=5*	*j=6*	*j=7*	*j=8*	*j=9*	*j=10*	*j=11*	*j=12*
$\hat{x}_j$	26,917	132,281	35,588	157,105	32,440	94,141	180,317	170,896	3,715	268,591	52,407	280,708

Table 3. Industry-by-industry technical coefficient matrix (**A**).

Industry	*j=1*	*j=2*	*j=3*	*j=4*	*j=5*	*j=6*	*j=7*	*j=8*	*j=9*	*j=10*	*j=11*	*j=12*
i=1	0.1130	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000	0.0917	0.0000	0.0000	0.0000	0.0000
i=2	0.0168	0.0618	0.0511	0.0458	0.0208	0.0930	0.0009	0.0120	0.0046	0.0009	0.0027	0.0023
i=3	0.0274	0.0016	0.0617	0.0018	0.0003	0.0006	0.0000	0.0263	0.0005	0.0001	0.0003	0.0011
i=4	0.0114	0.0042	0.0028	0.1569	0.0035	0.0028	0.0014	0.0038	0.0106	0.0110	0.0103	0.0096
i=5	0.0050	0.0042	0.0014	0.0012	0.1247	0.0016	0.0000	0.0041	0.0000	0.0001	0.0003	0.0003
i=6	0.0034	0.0004	0.0045	0.0036	0.0023	0.0614	0.0031	0.0022	0.0018	0.0036	0.0038	0.0030
i=7	0.0013	0.0011	0.0013	0.0129	0.0008	0.0128	0.1236	0.0017	0.0207	0.0092	0.0069	0.0035
i=8	0.0190	0.0093	0.0016	0.0046	0.0032	0.0027	0.0032	0.0001	0.0167	0.0052	0.0306	0.0195
i=9	0.0000	0.0001	0.0001	0.0000	0.0001	0.0001	0.0000	0.0000	0.0000	0.0000	0.0004	0.0001
i=10	0.0065	0.0066	0.0206	0.0066	0.0145	0.0065	0.0092	0.0124	0.0116	0.0474	0.0319	0.0077
i=11	0.0030	0.0007	0.0030	0.0038	0.0014	0.0032	0.0030	0.0024	0.0019	0.0031	0.0039	0.0029
i=12	0.0035	0.0017	0.0053	0.0045	0.0018	0.0194	0.0036	0.0028	0.0027	0.0036	0.0057	0.0150

Table 4. Interdependency matrix ($\mathbf{A}^*$).

Industry	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$	$j=6$	$j=7$	$j=8$	$j=9$	$j=10$	$j=11$	$j=12$
$i=1$	0.1130	0.0002	0.0000	0.0000	0.0003	0.0000	0.0000	0.5822	0.0000	0.0001	0.0001	0.0002
$i=2$	0.0034	0.0618	0.0138	0.0544	0.0051	0.0662	0.0012	0.0154	0.0001	0.0019	0.0011	0.0050
$i=3$	0.0207	0.0059	0.0617	0.0080	0.0003	0.0015	0.0002	0.1264	0.0001	0.0008	0.0004	0.0084
$i=4$	0.0020	0.0035	0.0006	0.1569	0.0007	0.0017	0.0016	0.0041	0.0003	0.0187	0.0034	0.0172
$i=5$	0.0042	0.0170	0.0015	0.0059	0.1247	0.0048	0.0002	0.0215	0.0000	0.0009	0.0004	0.0022
$i=6$	0.0010	0.0005	0.0017	0.0060	0.0008	0.0614	0.0059	0.0039	0.0001	0.0104	0.0021	0.0091
$i=7$	0.0002	0.0008	0.0002	0.0113	0.0001	0.0067	0.1236	0.0016	0.0004	0.0137	0.0020	0.0055
$i=8$	0.0030	0.0072	0.0003	0.0042	0.0006	0.0015	0.0033	0.0001	0.0004	0.0081	0.0094	0.0320
$i=9$	0.0001	0.0021	0.0008	0.0016	0.0008	0.0017	0.0024	0.0011	0.0000	0.0033	0.0052	0.0104
$i=10$	0.0006	0.0033	0.0027	0.0038	0.0018	0.0023	0.0062	0.0079	0.0002	0.0474	0.0062	0.0081
$i=11$	0.0015	0.0019	0.0021	0.0114	0.0009	0.0057	0.0105	0.0077	0.0001	0.0158	0.0039	0.0156
$i=12$	0.0003	0.0008	0.0007	0.0025	0.0002	0.0065	0.0023	0.0017	0.0000	0.0034	0.0011	0.0150

Table 5. Demand-based inoperabilities (Row 2) and equivalent dollar losses (Row 3) resulting from a 20% degradation in airline demand.

Industry	$j=1$	$j=2$	$j=3$	$j=4$	$j=5$	$j=6$	$j=7$	$j=8$	$j=9$	$j=10$	$j=11$	$j=12$
q_j	0.0003	0.0151	0.0005	0.0006	0.0015	0.2131	0.0017	0.0005	0.0004	0.0006	0.0013	0.0014
Loss ($)	$9M	$2B	$19M	$86M	$48M	$20B	$301M	$86M	$2M	$162M	$69M	$401M