Chapter 22

ANALYSIS OF INTERDEPENDENCIES BETWEEN ITALY'S ECONOMIC SECTORS

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Abstract The infrastructure sectors of developed countries have direct and indirect interdependencies. These interdependencies make national infrastructures extremely prone to the cascading effects of perturbations or failures. A negative event that reduces the operability of one infrastructure sector rapidly spreads to other sectors and back to the original sector in a feedback loop, amplifying the negative consequences throughout the national economy. This paper uses the Input-output Inoperability Model (IIM) to analyze interdependencies in Italy's economic sectors. Economic data from 1995 to 2003 provided by the Italian National Institute of Statistics (ISTAT) is used to investigate the interdependencies in 57 sectors. The results demonstrate that interdependencies between economic sectors have an overall increasing trend, which can dramatically enhance the negative consequences of any sector perturbation or failure.

Keywords: Italy, economic sectors, interdependencies, input-output inoperability model

1. Introduction

During the last two decades, for a variety of economic, social, political and technological reasons, significant changes have been seen in the organizational, technical and operational frameworks of practically every infrastructure sector in developed countries. Indeed, to reduce costs, improve quality and efficiency, and provide innovative services, infrastructure sectors have become highly interoperable. This enables infrastructure owners and operators to share common services and resources, and to better focus their efforts on their core businesses.

But this interoperability has increased the interdependencies between infrastructure components and sectors. Sector interdependence makes the entire national infrastructure prone to the cascading effects of perturbations or failures. A negative event that reduces the operability of one infrastructure sector can rapidly spread to other sectors and back to the original sector in a feedback loop, amplifying the negative consequences throughout the national economy.

Haimes and colleagues [3] proposed the Input-output Inoperability Model (IIM) to quantify the global impact of negative events in interdependent sectors. Their approach is based on the well-known theory of market equilibrium developed by Nobel laureate Wassily Leontief [5]. IIM uses Leontief's theoretical framework, but instead of considering how the provision of goods or services by one firm influences the levels of production of other firms, it focuses on the degradation of operability throughout a networked system. To this end, IIM introduces the notion of "inoperability," which is defined as the inability of a system to perform its intended functions.

IIM helps analyze how a given amount of inoperability of one component influences other components in a network. It is been used to evaluate the impact of a high-altitude electromagnetic pulse (HEMP) on the U.S. economy [2], to investigate economic losses due to a reduction in air transportation services [9], to study the recovery process in the aftermath of Hurricane Katrina [6], and to analyze the extent of cascading failures in a highly networked modern hospital compared with one that uses less information and communications technology [10]. IIM has also been extended to account for the spread of faults and the presence of uncertain data (using fuzzy numbers) [7].

This paper uses IIM to analyze interdependencies in Italy's economic sectors based on data from the period 1995 to 2003 provided by the Italian National Institute of Statistics (ISTAT). The results demonstrate that interdependencies between economic sectors have an overall increasing trend. Thus, any reduction in the operability of one sector – due to malicious acts, accidents or natural disasters – can cascade through all sectors, dramatically increasing the negative consequences to the country's entire economy.

2. Input-Output Inoperability Model

The Input-output Inoperability Model (IIM) is a theoretical framework for analyzing how interdependencies existing between different sectors of a complex society can propagate the spread of degradation [1, 3]. The framework requires each sector to be modeled as an atomic entity, whose level of operability depends on external causes as well as on the availability of "resources" supplied by other entities. An event (e.g., a failure) that reduces the operational capability of the i-th sector may induce degradations in other sectors that require goods or services produced by the i-th sector. The degradations may propagate to other sectors in a cascade effect, and can even exacerbate the situation in the i-th sector due to the presence of feedback loops.

IIM models this phenomenon using a level of inoperability associated with each sector. The inoperability of the i-th sector is expressed using the variable $x_i \in [0,\ 1]$. Note that $x_i = 0$ means that the i-th sector is fully operable, while $x_i = 1$ means that the sector is completely inoperable.

IIM evaluates the impact of external events that produce a given amount of inoperability using the dynamic equation:

$$\mathbf{x}(k+1) = \mathbf{x}(k) + \mathbf{K}\left[(\mathbf{\Lambda} - \mathbf{I})\,\mathbf{x}(k) + \mathbf{c}(k)\right] \quad (1)$$

where $\mathbf{x} \in [0, \ldots, 1]^n$ and $\mathbf{c} \in [0, \ldots, 1]^n$ are vectors specifying the levels of inoperability and external failure, respectively, that are associated with each of the n sectors considered in the scenario. $\mathbf{A} \in \mathcal{R}^{n \times n}$ is the matrix of Leontief coefficients and $\mathbf{K} \in \mathcal{R}^{n \times n}$ is the resilience matrix, which represents the capability of each sector to absorb the negative effects of a perturbation and its ability to restore the nominal conditions after a failure.

Matrix $\mathbf{\Lambda}$ can be decomposed into its main-diagonal and off-diagonal elements:

$$\mathbf{\Lambda} = diag\,(\mathbf{\Lambda}) + \mathbf{A} \quad (2)$$

where the first term models the restoring dynamics while matrix $\mathbf{A}$ models the functional dependencies existing between different sectors. Specifically, each entry a_{ij} of matrix $\mathbf{A}$ represents the influence of the inoperability of the j-th sector on the inoperability of the i-th sector. Obviously, when $a_{ij} < 1$, the i-th sector suffers a level of inoperability smaller than that exhibited by the j-th sector. On the other hand, when $a_{ij} > 1$, there is an amplification in the inoperability level.

Limiting the study to impact analysis, we can omit the first term in Equation 2. Then, assuming $\mathbf{K} = \mathbf{I}$, as proposed in [1], Equation 1 reduces to:

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{c} \quad (3)$$

where $a_{ii} = 0 \;\forall\; i = 1, \ldots, n$.

To evaluate the dependency of each sector with respect to the others, we introduce a "dependency index," which is defined as the sum of the Leontief coefficients along a single row:

$$\delta_i = \sum_{j \neq i} a_{ij} \qquad \text{(row summation)} \quad (4)$$

The dependency index δ_i measures the resilience of the i-th sector. When the index is less than 1, the i-th sector preserves some working capabilities (e.g., because of stocks, buffers, etc.) despite supplier inoperability. On the other hand, when $\delta_i > 1$, the operability of the i-th sector may be completely nullified even when some of its supplier sectors have residual operational capabilities.

The influence that a sector exercises on the entire system is expressed by its "influence gain," i.e., the column sum of the Leontief coefficients:

$$\rho_j = \sum_{i \neq j} a_{ij} \qquad \text{(column summation)} \quad (5)$$

A large value of ρ_j means that the inoperability of j-th sector induces significant degradation to the system. When $\rho_j > 1$, the negative effects (in terms of inoperability) induced by cascading phenomena on the other sectors are amplified. The opposite occurs when $\rho_j < 1$.

Note that parameters defined in Equations 4 and 5 represent one-step-ahead estimations, and the overall consequences have to be evaluated based on a steady-state solution to Equation 3. When the constraints on x_i are satisfied, the closed form solution is given by:

$$\overline{\mathbf{x}} = \mathbf{G}^{-1}\mathbf{c} \qquad \text{where } \mathbf{G} = (\mathbf{I} - \mathbf{A})\,. \tag{6}$$

The entries g_{ij} of $\mathbf{G} \in \mathcal{R}^{n\times n}$ represent the consequences (in terms of induced inoperability) that an external event affecting the j-th sector has on the i-th sector. The term g_{ii} represents the amplification of inoperability registered by the i-th sector due to feedback with respect to the amount of inoperability directly induced by the external cause c_i.

3. Economic Formulation of IIM

The most difficult task when applying IIM is to estimate the Leontief coefficients. In [1] the coefficients were evaluated using U.S. economic statistics provided by the Bureau of Economic Analysis. This paper follows a similar approach using data on the Italian economy supplied by ISTAT [4].

ISTAT recently released the input-output tables for the Italian economy during the period 1995 to 2003. The data was grouped into 59 sectors in accordance with the European Sec95 Standard [4]. We use the ISTAT data, but restrict our analysis to 57 sectors because two sectors (Extraction of Uranium and Thorium Minerals, and Domestic Services) have no dependencies and influences on the other sectors. The ISTAT data included the **U** (*Use*) and **S** (*Supply*) matrices for each year from 1995 to 2003. These commodity-per-industry matrices represent the amount of goods used (**U**) and services provided (**S**) by each economic sector expressed in millions of Euros.

Due to the symmetry of the ISTAT data, the main-diagonal elements of the *Use* and *Supply* matrices correspond to the commodities directly used and provided by each sector, respectively. The off-diagonal elements capture the functional dependencies existing between sectors.

Over the 1995–2003 period, the *Supply* matrix has uniform increments for the main-diagonal entries and the total volumes. The *Use* matrix, which is illustrated in Figure 1, shows considerable increments for the off-diagonal elements, which confirms the increased relevance of cross-sector relationships.

Starting with the ISTAT data and using the technique described in [1], we calculated the Leontief coefficients for the $\mathbf{\Lambda}$ matrix. The normalized matrices $\mathbf{U}^*$ and $\mathbf{S}^*$ were first computed using the equations:

$$u^*_{ij} = \frac{u_{ij}}{\sum_{i=1}^{n} u_{ij}} \qquad s^*_{ij} = \frac{s_{ij}}{\sum_{i=1}^{n} s_{ij}}. \tag{7}$$

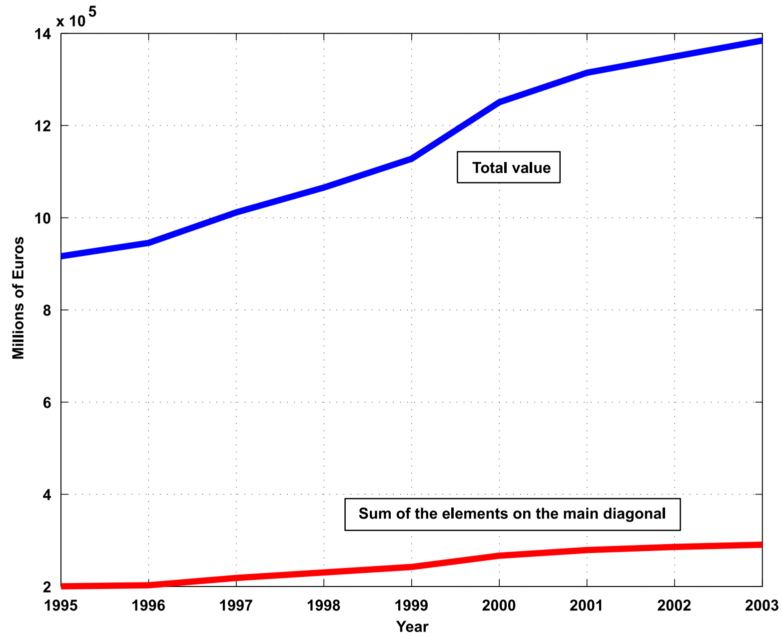

Figure 1. *Use* matrix values (1995 to 2003).

The Leontief coefficients were then calculated using the normalized matrices:

$$\mathbf{\Lambda} = \left(\mathbf{S}^{*T}\right)\mathbf{U}^{*}. \tag{8}$$

Having computed the Leontief coefficient matrix in Equation 8, the matrix $\mathbf{A}$ was obtained by nullifying the elements on the main diagonal.

Figure 2 shows the dependency indices for the 57 sectors in the Italian economy. The sectors that are more dependent on other sectors have larger dependency index values. The most dependent sectors are Building (Id = 33), Wholesale Trade (Id = 35), Retail Trade (Id = 36) and Public Administration (Id = 51). Although there are no dramatic variations in the indices for different sectors over the time period, the values are slightly reduced for the Building (Id = 33) and Wholesale Trade (Id = 35) sectors, while the values for the other sectors show increments. Note that 18 sectors (19 sectors in 2003) have dependency index values close to 1 or greater. This means that the operability levels of these sectors largely depend on external resources; therefore, they can have dramatic degradations due to domino effects.

On the other hand, the influence gain values (Figure 3) are very stable from 1995 to 2003. The largest values are assumed by the Wholesale Trade (Id = 35), Retail Trade (Id = 36) and Terrain Transportation (Id = 38) sectors, with peak values ranging from 1.2 to 1.6. Moreover, 19 sectors (20 sectors in 2003) have influence gain values greater than 1. This implies that the consequences,

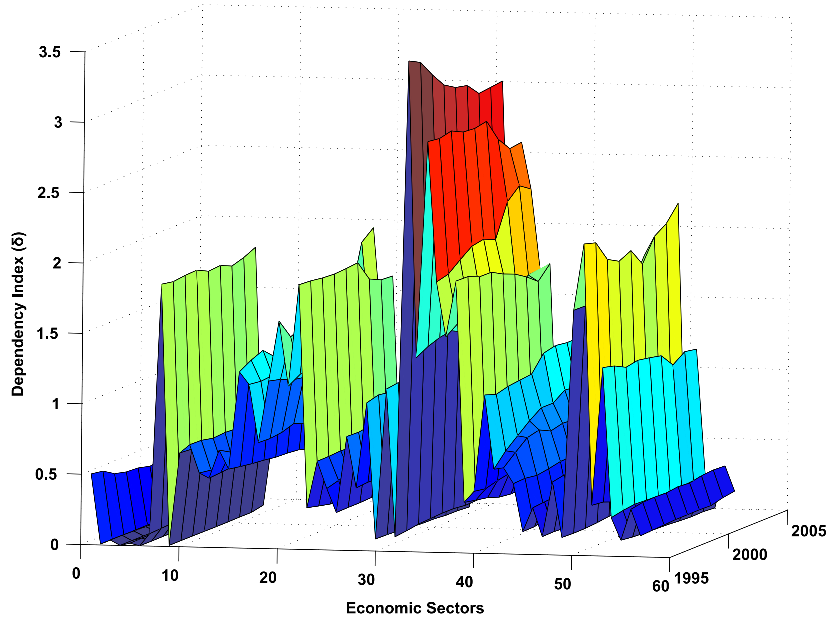

Figure 2. Dependency indices (δ_i) for the 57 sectors (1995 to 2003).

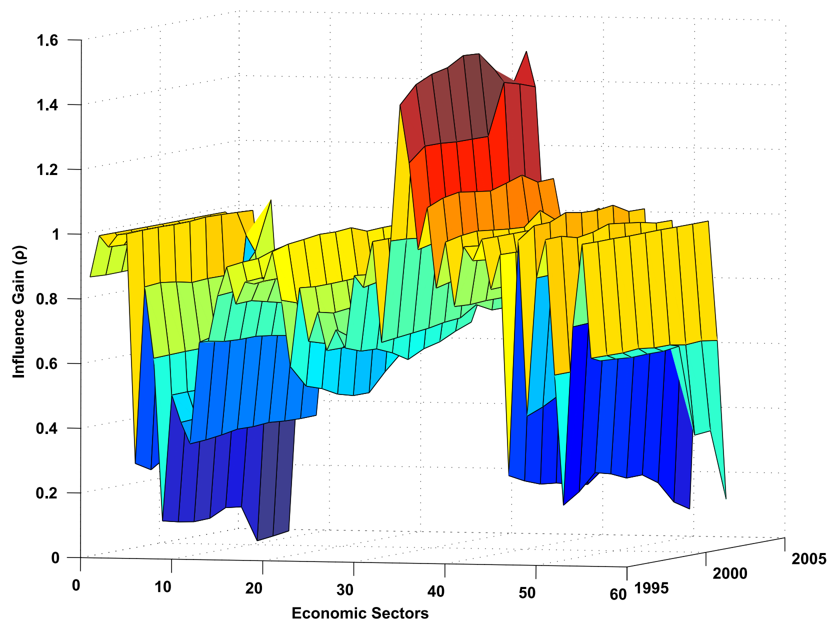

Figure 3. Influence gains (ρ_i) for the 57 sectors (1995 to 2003).

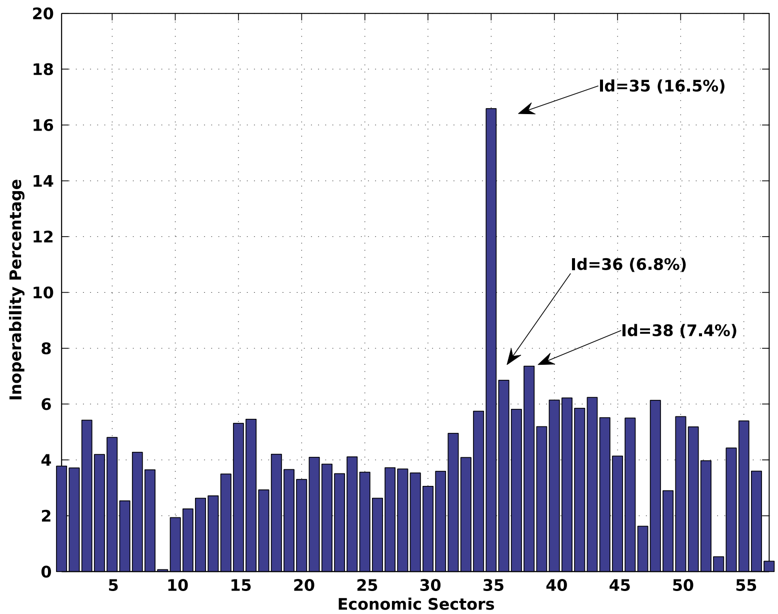

Figure 4. Sector inoperability at steady state given an initial perturbation (2003).

in terms of inoperability, induced on the entire system are more than double those that are produced directly by external causes.

It is important to note that the indices discussed above provide only one-step-ahead information. Therefore, to estimate the overall consequences induced by external failures, it is necessary to solve Equation 3.

4. Application of Dynamic IIM

Equation 3 above must be solved to estimate the overall system impact of an external event that reduces the operability of a single sector. If we assume that all the variables are constrained in their domains of definition, then Equation 6 provides the corresponding steady-state solution in closed form.

Figure 4 shows the levels of inoperability attained by the various sectors when the Wholesale Trade sector (Id = 35) is externally perturbed to reduce its operability by 10%. As noted above, due to cascade effects, this perturbation affects almost every sector quite substantially: 19 sectors have levels of inoperability greater than 5% and only four sectors have levels of operability greater than 98%. Moreover, due to feedback effects, the level of inoperability of the Wholesale Trade sector grows to 16.5%. The most degraded sectors, as predicted by their large dependency index values, are Terrain Transportation (Id = 38) and Retail Trade (Id = 36), which reach inoperability levels of 7.4% and 6.8%, respectively. This analysis clearly demonstrates that sector interdependencies can significantly affect the overall consequences of a negative event.

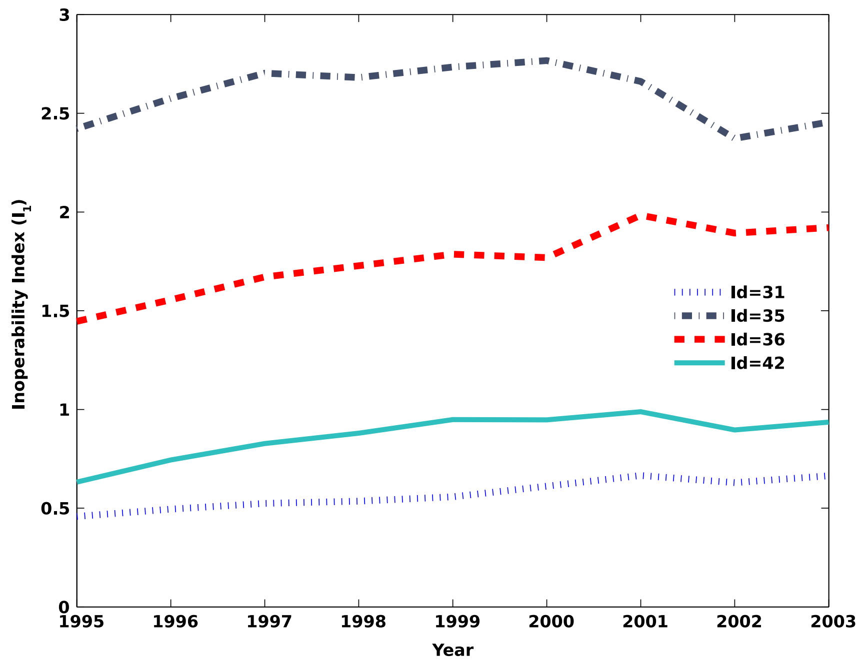

Figure 5. Overall inoperability index for a 10% perturbation (1995 to 2003).

A global index is required to codify the impact of a perturbation on the entire system. The simplest index, which we call the "overall inoperability index," is defined as:

$$I_1^{year}(I_d = \alpha) = \sum_{i=1}^{57} \overline{x}_i. \tag{9}$$

The index is the sum of the inoperability levels (at steady state) over all sectors for a given year given a perturbation of I_d with amplitude α.

Figure 5 shows that the same perturbation produces a different effect for each year in the period from 1995 to 2003. The same initial perturbation of 10% is applied to each sector (Energy (Id = 31), Wholesale Trade (Id = 35), Retail Trade (Id = 36), and Post and Communications (Id = 42)). Note that the index increases uniformly during the period. In the years when interdependencies between sectors increase, the entire system becomes much more fragile. An abrupt change in the trend is seen in 2002, most likely due to the impact of the 9/11 attacks on the world economy.

The overall inoperability index provides a global measure, but it gives the same weight to every economic sector, discounting the relative importance of each sector in the national economy. To address this issue, we define an index,

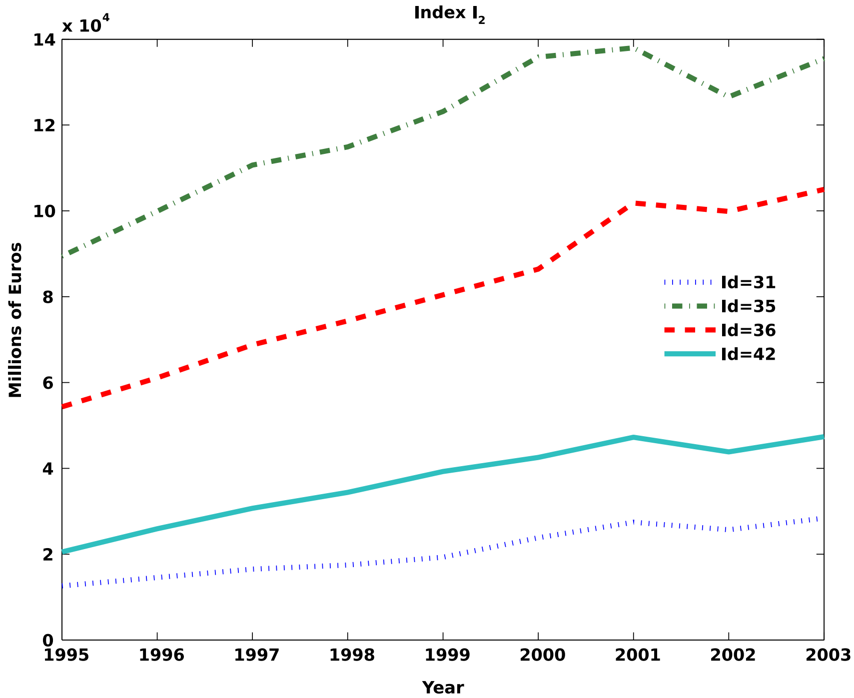

Figure 6. Weighted inoperability index for a 10% perturbation (1995 to 2003).

which is normalized with respect to the economic value of each sector. This "weighted inoperability index" is defined as:

$$I_2 = \sum_{i=1}^{57} \left[\left(\sum_j s_{ij} \right) \overline{x}_i \right]. \tag{10}$$

The index weights the inoperability of each sector based on the sum of corresponding row in the *Supply* matrix.

Figure 6 shows the weighted inoperability index for each year in the period from 1995 to 2003. Once again, the data is generated by applying the same initial perturbation of 10% to each sector (Energy (Id = 31), Wholesale Trade (Id = 35), Retail Trade (Id = 36), and Post and Communications (Id = 42)). The trend in the overall level of inoperability is the same as in Figure 5. Note also that the same results are obtained when the inoperability of a sector is weighted according to the sum of its corresponding row in the *Use* matrix.

5. Conclusions

The Input-output Inoperability Model (IIM) is a powerful approach for investigating the interdependencies existing between various sectors of a national economy. Our study, which analyzes data from Italy's 57 economic sectors, reveals an increasing trend of interdependence between sectors. The presence of these interdependencies significantly amplifies the system-wide propagation of negative effects due to a perturbation or failure in just one sector.

However, several points should be considered to correctly interpret the results of the analysis. In the classical Leontief model, it is reasonable to assume that the importance of a sector is proportional to the economic value of exchanged goods or services, but this assumption may not be entirely valid in the case of inoperability. For example, a resource with low economic value (e.g., cooling water for a nuclear reactor) is mandatory from an operational point of view. Also, the Sec95 categories used in this work may be somewhat inadequate for modeling interdependency phenomena; this is because components with very different behaviors are grouped in the same sector. Other limitations are that the model assumes that all the variables reach their steady-state values in a time period compatible with the time horizon, and that all the sectors have the same dynamics (i.e., the inoperability evolves with the same time scale in every sector). Finally, the normalization process (Equation 8) forces the Leontief coefficients to be no greater than one; this prevents the model from modeling amplifications in inoperability transmission.

These considerations suggest that the IIM results should be compared with those obtained using other approaches. A promising strategy has been proposed by Rosato, *et al.* [8], where the "macroscopic" coefficients are calculated on the basis of correlations existing among detailed topological models of each pair of sectors. Another approach is to obtain values for the coefficients by conducting interviews with experts from each sector. The comparison of the results of these and other approaches is the subject of our future research.

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