Economic impact assessment of Critical Infrastructure failure in the EU: A combined Systems Engineering – Inoperability Input-Output Model

Olaf Erik Jonkeren*, David Ward, Bogdan Dorneanu, Georgios Giannopoulos

*European Commission, Joint Research Centre, Institute for the Protection and Security of the Citizen, Ispra, Italy

ABSTRACT

The European Programme on Critical Infrastructure Protection (EPCIP) of the European Commission is in search for a methodology to analyse economic consequences of critical infrastructure failure in the European Union. Therefore, a combined Systems Engineering and Inoperability Input-Output model (SE-IIM) is being developed. To illustrate the functioning of this model, the economic losses as a result of the 2003 Italian electricity infrastructure outage are analysed for both, the full system of economic industries and for a subsystem of 11 Critical Infrastructure (CI) industries. Economic losses are estimated on the national level and on the regional level (the north, center and south of Italy and for Sicily). Firstly, the systems engineering model analyses the performance degradation and recovery of the power system, as a result of failure and repair propagation. Secondly, economic losses are estimated with the IIM using Eurostat I-O data for Italy (industry-by-industry type) and the information obtained in the SE model.

The IIM is able to analyse how the initial perturbation impacting on the electricity industry propagates into the economic system due to the existence of economic interdependencies. Applying the IIM to the full system of 56 industries results in a rough estimate of the economic losses: €81.79 million for the 11 CI industries and €123.17 million for all industries together. We conclude that the SE model is a simple tool of getting a rough picture of the phenomena that take place inside the considered system. The strength of the IIM for our purpose is that it can be applied to a complete system of industries, representing the economy of a region or country but one can also zoom in into a subsystem of industries. In addition, I-O data for every EU Member State is available. Further improvements and extensions of the SE-IIM model are foreseen.

1. INTRODUCTION

This paper shows a model for analyzing interdependencies and economic consequences of infrastructure failure in the EU. The Joint Research Centre (JRC) supports European Policies in the domain of critical infrastructures protection that is part of the European Programme for Critical Infrastructure Protection (EPCIP). The legislative tool of EPCIP is the Council Directive 2008/114/EC on the identification and designation of European Critical Infrastructures and the assessment of the need to increase their protection. Currently within the scope of the Directive, only energy and transport infrastructures have been identified as European Critical, although EPCIP covers a lot more than this. The relevant sectors and subsectors that are covered by the aforementioned Directive can be depicted in Table 1.

Table 1: List of ECI sectors in Council Directive 2008/114/EC

Sector	Subsector	
I. Energy	1. Electricity	Infrastructures and facilities for the generation and transmission of electricity in respect of the supply of electricity.
	2. Oil	Oil production, refining, treatment, storage and transmission by pipelines.
	3. Gas	Gas production, refining, treatment, storage and transmission by pipelines. LNG terminals.
II. Transport	4. Road transport 5. Rail transport 6. Air transport 7. Inland waterways transport 8. Ocean and short-sea-shipping, and ports	

The identification and designation of European Critical Infrastructure is a four-step procedure whose last step is fulfilling the thresholds set on the cross-cutting criteria which are the following: (1) the casualty's criterion (number of fatalities), (2) the economic effects criterion (economic loss) and (3) the public effects criterion (impact on public confidence, physical suffering). More details on the Directive can be found in European Commission (2008).

The methodology applied in the current study is a combined systems engineering-economic inoperability Input-Output model (SE-IIM). In our application of this model, the economic losses as a result of a hazard, for a set of 11 CI industries are analysed. Firstly, the systems engineering model analyses the performance degradation and/or recovery of the system, as a result of failure and repair propagation.[1] Secondly, economic losses are estimated with the IIM using the information obtained in the SE model. With an IIM, economic losses are valued according to the Leontief production function (inputs are used in fixed proportions). It estimates the consequences of an interruption through lost production.[2]

So, economic losses are considered as losses resulting from the absence of resources. Both these phenomena, the presence of failures and the absence of resources, may propagate their consequences and impact on the system. For another illustration of this concept, see Panzieri and Setola (2008).

In the current study, the combined model is applied to a system of CI's in several regions in Italy. Dynamic phenomena taking place in a complex system, such as the Italian electricity transmission network, are often unpractical to model in a rigorous way. The need to couple the SE model with a model able to assess the economic consequences of a failure of this system requires some simplification, in order to make the results easy to obtain and interpret. This is the main goal of the SE model: a simplified, yet adequate representation of the system to be analysed.

An attractive feature of the IIM is its ability to incorporate the workforce into the analysis (Anderson et al., 2007), so that also economic losses following from perturbations to this 'industry' can be analysed. Because the importance of workforce in the context of economic loss analysis is emphasized several times in the literature (Santos and Haimes, 2004; Ferrari et al., 2011) this feature is exploited further in the current study as well.

Economic losses are defined as direct and indirect flow losses (or business interruption losses) in this study. In economics, flows refer to the services or outputs of stocks over time while stocks refer to a quantity at a single point in time. Property damage represents a decline in stock value and usually leads to a decrease in service flows. Flow losses originate only in part from a company's own property damage and can occur without the presence of property damage (Rose, 2009). Both, stock damage and flow effects can be of a direct or an indirect nature. Direct effects are suffered by the sector that is hit by a particular hazard. Indirect effects impact on sectors that are located in the close vicinity of the initially hit sector

[1] As an example of failure propagation, an explosion, which often propagates to spatially located elements, can be mentioned.

[2] Because there is no market where production interruptions (of goods or services) are traded, there is no market price that shows the marginal cost per time unit of supply interruption. Therefore, economists have developed several methods for calculating the effects of a supply interruption, the production function approach being one of them. See for example De Nooij et al. (2007) for a summary on these methods.

(indirect stock damage) or that are dependent on the initially hit sector through supply and demand relationships (indirect flow effects). Table 2 summarizes this paragraph on the different types of economic impact.

Table 2: Classification of economic impacts

	Stock damage	Flow effects/ losses
Direct	Property damage in hit sector	Business interruptions in hit sector
Indirect	Via hazardous material releases from originally hit sector	Via suppliers/ customers relations

Input-Output (I-O) models, and thus the IIM ignore stock damages and only take into account direct and indirect flow losses. Note that including both stock damages and flow losses would result in double counting. The value of an asset is the discounted flow of net future returns from its operation. So, suppose a machine with a 1-year lifespan were destroyed. Then the economic loss is equal to either the value of a new machine with a 1-year lifespan or the discounted flow of not produced output for one year (Rose and Lim, 2002).

Economic sectors may be able to withstand an external impact to a certain extent implying these sectors own a certain level of resilience. In the context of economic impact analysis, static economic resilience is defined as the ability of a system to maintain function when shocked. Static means that this type of resilience ignores repair and reconstruction activities. Dynamic resilience, on the other hand, is the speed at which an entity or system recovers from a shock (Rose, 2009). I-O analysis is severely limited in modeling most aspects of resilience to hazards at the firm, the market, or the regional economy level.[3] Therefore, this approach is generally expected to only provide the upper-bound estimates of losses (Rose and Liao, 2005). However, Rose and Lim (2002) also show how output losses obtained by an I-O model can be adjusted (downward) for different types of measures that improve static resilience.

The approach followed in the present paper, responds to an expressed need from EU member states, operators and relevant authorities for a high level analysis of critical infrastructures without going too much in the details of the various infrastructure assets. It is more towards a systems approach for critical infrastructures that focuses on the cascading effect and the impact of the event without performing detailed analysis in each asset of the

[3] The presence of excess stocks at firms to withstand an interruption of production is not incorporated into the I-O data.

infrastructure but rather at a certain level of abstraction that is still reasonable for obtaining a valid representation of the infrastructure and the dynamics of the event. The advantage of such an approach is that the conclusions and the lessons learned from the present analysis can be eventually extrapolated to other cases of critical infrastructure disruption in different countries assuming that a high level representation of these infrastructures (especially when these are interconnected with the ones of the neighbouring countries) should follow the same principles.

In the next section, the theoretical framework of the systems engineering model and the IIM will be described. In section 3, the applicability of the model for the purpose of a case study, the 2003 power blackout in Italy, will be discussed. The last section concludes.

2. MODEL DESCRIPTION

2.1. Systems engineering model

In electrical power systems, a great variety of different dynamic processes take place. These dynamic phenomena have different physical origins and they occur in different time scales. Modelling all of these is however not practical in most cases. Relevant and adequate simplifications are often beneficial for analysing the system, as well as for obtaining results, which are easy to understand and interpret. A commonly used approach for assessing CI's is based on complex network concepts. A CI (for example, a power system) is abstractly modelled as a network of nodes interconnected by links (Rigole and Deconinck, 2006; Wilde and Warren, 2008). The nodes (depicted by numbers in Figure 1) can be a sub-network in their own respect, with nodes and links ($L_{i,j}$). Where *i* is the source node and *j* the sink node.

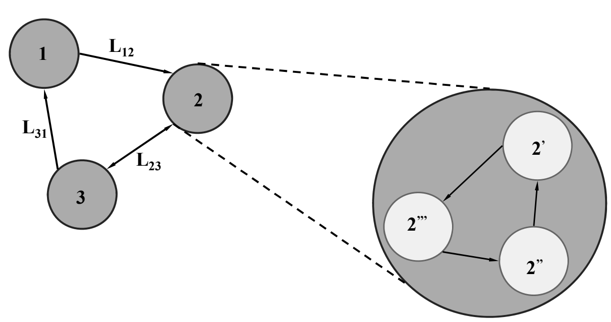

Figure 1: Network representation of a system

In the following, the behavior of the system is modeled by applying the conservation principles of the resources of the system. It is considered that a resource, *R*, is conserved inside the system, although it may change its amount. The conservation of the resource signifies that what enters the system should leave, is transformed into another quantity, or it accumulates in the system. The conservation equation, typically an ordinary differential equation, is written in a general form as:

$$\left\{ \text{Accumulation} \right\} = \left\{ \text{Resource in} \right\} + \left\{ \text{Resource out} \right\} + \left\{ \text{Generation} \right\} - \left\{ \text{Consumption of resource} \right\} \quad (1)$$

The conservation equation is applied to the full system, or to each of the networks nodes.

2.2. Inoperability Input-Output model

The inoperability I-O model is derived from Wassily Leontief's I-O model of the economy (Leontief, 1951a; 1951b). The formulation of the original I-O model is given in Equation 2, where x_i represents the total production output of industry i. The technical coefficient a_{ij} represents the ratio of the input from industry i to industry j and the overall production requirements of industry j. c_i indicates the final demand of the i^{th} industry.

$$x = Ax + c \qquad \left\{ x_i = \Sigma_j \, a_{ij} x_j + c_i \right\} \quad (2)$$

Taking this classic model as a starting point, Santos and Haimes (2004) proposed the demand-reduction IIM using the following formulation:

$$q = A^{*} q + c^{*} \quad (3)$$

where q is the inoperability vector expressed in terms of relative loss. The elements of the vector **q** represent the ratio of unrealized production with respect to the "as-planned" production level of the industry sectors. $\mathbf{A}^{*}$ is the interdependency matrix that indicates the degree of coupling of the industry sectors. The elements in a particular row of this matrix (see Equation 4) tell how much additional inoperability is contributed by a column industry to the row industry. Finally, $\mathbf{c}^{*}$ is a demand-side perturbation vector expressed in terms of relative degraded final demand.

$$\boldsymbol{A^*} = \begin{pmatrix} a_{11}\left(\frac{x_1}{x_1}\right) & \ldots & a_{1j}\left(\frac{x_j}{x_1}\right) & \ldots & a_{1n}\left(\frac{x_n}{x_1}\right) \\ \vdots & & & & \\ a_{i1}\left(\frac{x_1}{x_i}\right) & \ldots & a_{ij}\left(\frac{x_j}{x_i}\right) & \ldots & a_{in}\left(\frac{x_n}{x_i}\right) \\ & & & & \\ a_{n1}\left(\frac{x_1}{x_n}\right) & \ldots & a_{1n}\left(\frac{x_j}{x_n}\right) & \ldots & a_{nn}\left(\frac{x_n}{x_n}\right) \end{pmatrix} \tag{4}$$

Equation 3 is rewritten as:

$$q = (I - A^*)^{-1}\, c^* \tag{5}$$

Let us then define $(\mathrm{I} - \mathrm{A}^*)^{-1}$ as $\mathbf{B}^*$. Supposing that $\mathbf{B}^*$ can be found ($\det(\mathrm{I} - \mathrm{A}^*)^{-1} \neq 0$), the elements b_{ij} of $\mathbf{B}^*$ represent the overall inoperability transmission, i.e., how much of the inoperability injected in the system by an external failure c_j is transmitted to the *i*th infrastructure taking into account first-, second- and higher order dependencies. Note that this is different from the elements a_{ij} of matrix **A**, which only take into account direct influences.

To finally estimate the economic losses $\boldsymbol{\delta x}$, the inoperability of sector i (q_i) is multiplied with its corresponding "as-planned" production (x_i), which is:

$$\delta x = diag(q)\; x \tag{6}$$

Where *diag(q)* is a diagonal matrix formed from **q**.

3. MODEL APPLICATION

3.1. Case study description

As an example for applying the procedure presented above, the Italian power blackout on September 28, 2003 affecting the whole country and cutting service to about 45 million people, is used. Electricity was not supplied for a time interval ranging from 1.5 hours in the northern part of Italy to 18 hours in Sicily (Sforna and Delfanti, 2006). The events on the evening of 28 September 2003 began at 03:01 a.m. Due to a sequence of line tripping in the following 25 minutes, the Italian grid separated from the Union for the coordination of

Transmission of Electricity (UCTE), now European Network of Transmission System Operators for Electricity (ENTSO-E) and at 03:28 a.m., went into general blackout.

3.2. Systems engineering model

The time zero of the modeling procedure is assumed the moment the events began (3:01 a.m. of 28 September 2003). The cascading events that lead to the separation of the grid from UCTE and the total blackout will not be considered further, since their impact on the economic assessment is assumed small. The focus of the modeling is on the restoration stages that followed, since the duration of this process is much longer than the one of the network failure stage.

Some studies (Rosato et al., 2007; Rocco et al., 2012) have modeled the Italian high-voltage electrical transmission grid (IHVETG) as an undirected graph of 127 nodes and 171 links. Others (Rosato, 2011) used 310 nodes and 361 links. For the purpose of our study, the Italian network is split into four sub-sets, as shown in Figure 1a:

a) North, including the following regions: Aosta Valley, Piedmont, Liguria. Lombardia, Friuli-Venezia Giulia, Trention-Alto Adige and Veneto;
b) Centre, that includes Emilia-Romagna, Tuscany, Umbria, Lazio, Marche, Abruzzo, Molise and Sardegna;
c) South, formed of Campania, Basilicata, Puglia and Calabria;
d) Sicily.

This simplification considerably reduces the size of the problem, since the network is reduced to only four nodes, corresponding to the regions described above. The connections of the IHVETG with the following countries are also considered: France, Switzerland, Austria, Slovenia and Greece. The requirements and the exchanges of each of these sub-networks with these neighboring countries and amongst themselves are shown in Figure 1b.

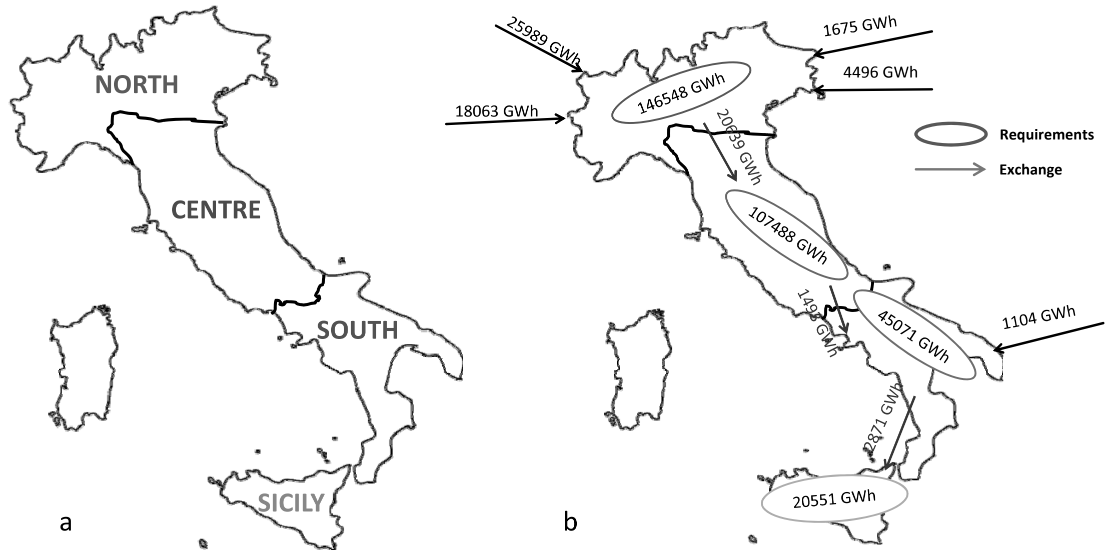

Figure 1: a) Split of the Italian grid for the analysis of the economic impact; b) Requirements and exchanges for the considered sub-sets

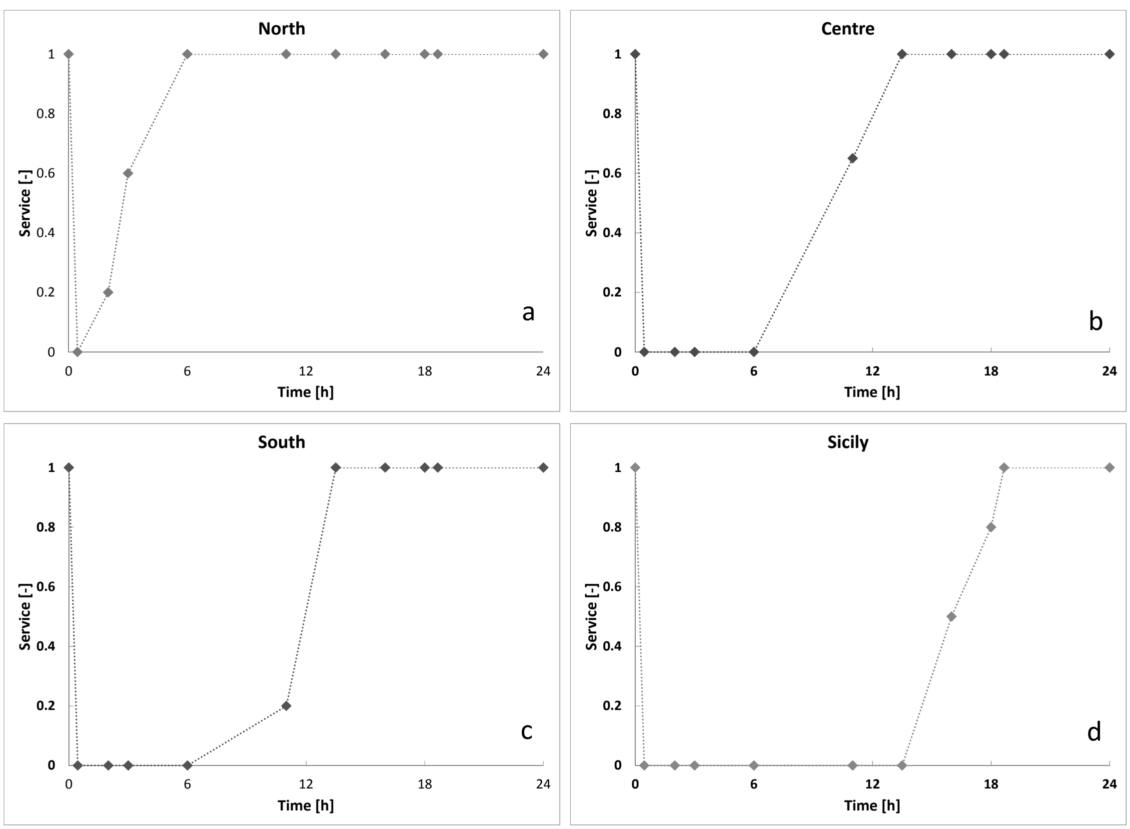

Figure 2: Results for the service availability for the four sets during the restoration process: a) North; b) Centre; c) South; d) Sicily

The data is taken from GRTN (2004). Further, the conservation equation 1 is applied to each node. The North region is the first one to be connected to the French and Slovenian grid, followed by the reconnection with the Centre and South regions. Additionally, the connection with Greece has been restored. Sicily is the last region to be connected.

The restoration stage started at 03:28 a.m. and lasted until 09:40 p.m. (Berizzi, 2004). The application of this model leads to the results in Figure 2. As expected, the four regions resume service at different speeds. The Northern region resumes full service after about six hours (Figure 2a), followed by the Centre (Figure 2b) and the South (Figure 2c) after about thirteen hours. The last region to resume normal operation is Sicily (Figure 2d). These records are in good agreement with the data available from the UCTE (2004) for the North and Centre part of the Italian grid. The low information availability on the South and Sicily did not allow for a comparison for these regions.

3.3. Inoperability Input-Output model

The Eurostat I-O data for the year 2005 is used to analyse the effect of an initial perturbation to a CI, on its related CI's in the four regions in Italy, as defined in the previous section. The data is of the industry-by-industry type and considers 56 industries in total on the national level. For this case study, 11 out of the 56 industries that can be identified as critical infrastructures were selected in order to analyse the effects for a subsystem of CI's. Several of the Eurostat sub-industries can be merged into the industries as considered by the Directive in Table 1. They are presented in Table 3.

Table 3: Selected industries

No.	Eurostat industry	CI industry Directive
1	Manufacture of coke, refined petroleum products and nuclear fuels	Energy
2	Electricity, gas, steam and hot water supply	
3	Land transport; transport via pipelines	Transport
4	Water transport	
5	Air transport	
6	Post and telecommunications	Telecommunication
7	Financial intermediation, except insurance and pension funding	Finance
8	Insurance and pension funding, except compulsory social security	
9	Activities auxiliary to financial intermediation	
10	Health and social work	Health
11	Workforce	Workforce

By selecting 11 out of the 56 industries for calculating the inoperability vector **q**, the case study assumes that the excluded 45 industries are exogenous to the interdependency matrix

$\mathbf{A}^*$. So, due to the omission of other cross-industry impacts, the inoperabilities calculated (the entries in vector **q**) and shown for the 11-industry system are lower than what they should be when taking into account all 56 industries. However, the question is to what extent this really is a shortcoming of focusing on a subsystem. Recently, in an empirical study, van Eeten et al. (2011) found that the validity of the idea that there is a vast web of dependencies across CI's which allow cascading failures to propagate quickly, is questionable. The authors find only a small number of focused, unidirectional pathways around two infrastructures: energy and telecommunications. Focusing on only a few, likely dependent industries, like in this study, can therefore be justified. Table 4 represents the 11×11 interdependencies ($\mathbf{A}^*$) matrix for the national level which describes the transmission of inoperability from the CI industries in the columns to the CI industries in the rows. In line with van Eeten et al. (2011), the large majority of the entries in Table 4 show very small values for inoperability transmission. In our study however, the CI industries that are most connected in the system are land transport, finance and workforce (these industries have relatively many high values in their columns).

In this analysis, the four $A^*_{regional}$ matrices (that represent interdependencies between the CI industries within the four regions) will be the same for every region and equal to the national A^* matrix (as is also done in, for example, Anderson et al. (2007)). Therefore, it is assumed that at regional level the same interdependencies between industries exist as at national level (the magnitude and the pattern of inoperability transmission in the system is the same on both geographical levels). On the one hand, from a mathematical/modeling perspective, as the A^* matrix (in the IIM model) is derived from the A matrix[4] this assumption is quite strong. Firstly, it implies that the regional producers use the same 'production recipes' as producers on the national level. Secondly, that relative export and import levels for producers at the regional level are equally high as for producers at the national level. This second result is unlikely, as producers are likely to depend more on exports and imports as the geographical area in which they are considered to operate decreases.[5] Therefore, while the size of the technical coefficients should drop when a smaller geographical entity is considered (Miller and Blair, 2009), in our study these coefficients do not change. On the other hand, from the perspective of the functioning of large infrastructure networks, using the national A^* matrix also on the regional level can be justified by arguing that CI networks are national

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[4] In other words, as the interdependencies are derived from information on economic transactions/ flows between industries.

[5] Said differently, even though the geographical area for analysis has shrunk, producers are still able to obtain the same share of resources from within the region (Miller and Blair, 2009, p. 71).

networks. As a result, a failure will have more or less the same repercussions in terms of inoperability for other industries throughout the country.

In order to obtain the matrix $\mathbf{B}^*$, which represents overall inoperability transmission in the system, the $\mathbf{A}^*$ matrix is transformed using $(I - A^*)^{-1}$. The result can be found in Table 5.

Table 4: IIM matrix A^* (representing first order interdependencies) for the selected industries

Indus.	1	2	3	4	5	6	7	8	9	10	11
1	0.0668	0.0313	0.1248	0.0030	0.0261	0.0051	0.0017	0.0001	0.0026	0.0061	0.3572
2	0.0073	0.1426	0.0133	0.0002	0.0002	0.0107	0.0041	0.0004	0.0020	0.0151	0.2695
3	0.0051	0.0069	0.0665	0.0020	0.0029	0.0105	0.0018	0.0008	0.0016	0.0086	0.2762
4	0.0154	0.0249	0.0209	0.0045	0.0003	0.0010	0.0003	0.0000	0.0006	0.0023	0.3425
5	0.0021	0.0028	0.0223	0.0101	0.0114	0.0385	0.0229	0.0010	0.0105	0.0011	0.4742
6	0.0054	0.0150	0.0336	0.0014	0.0036	0.0234	0.0367	0.0050	0.0119	0.0186	0.3300
7	0.0062	0.0105	0.0371	0.0015	0.0014	0.0148	0.0846	0.0291	0.0200	0.0121	0.2227
8	0.0019	0.0025	0.0267	0.0026	0.0040	0.0056	0.0219	0.0006	0.0022	0.0051	0.7289
9	0.0003	0.0011	0.0035	0.0002	0.0001	0.0037	0.3053	0.3581	0.1569	0.0035	0.0516
10	0.0000	0.0001	0.0001	0.0000	0.0000	0.0003	0.0001	0.0000	0.0000	0.0626	0.1626
11	0.0016	0.0058	0.0233	0.0015	0.0014	0.0114	0.0297	0.0030	0.0046	0.0580	0.0000

Note: Table 3 indicates to which industry the numbers in the first column and first row refer to.

Table 5: IIM matrix B^* (representing first, second and higher-order interdependencies)

Indus.	1	2	3	4	5	6	7	8	9	10	11
1	1.0740	0.0445	0.1585	0.0046	0.0296	0.0149	0.0219	0.0051	0.0074	0.0392	0.4753
2	0.0102	1.1699	0.0283	0.0009	0.0012	0.0176	0.0193	0.0042	0.0055	0.0413	0.3478
3	0.0068	0.0117	1.0819	0.0028	0.0039	0.0160	0.0150	0.0040	0.0045	0.0308	0.3240
4	0.0178	0.0330	0.0359	1.0053	0.0015	0.0067	0.0145	0.0029	0.0035	0.0275	0.3824
5	0.0043	0.0093	0.0428	0.0114	1.0128	0.0478	0.0511	0.0107	0.0176	0.0371	0.5420
6	0.0076	0.0223	0.0515	0.0024	0.0048	1.0307	0.0611	0.0148	0.0185	0.0470	0.3992
7	0.0087	0.0172	0.0560	0.0025	0.0027	0.0219	1.1146	0.0439	0.0288	0.0358	0.3201
8	0.0043	0.0099	0.0521	0.0041	0.0056	0.0167	0.0534	1.0077	0.0086	0.0557	0.7841
9	0.0056	0.0127	0.0490	0.0030	0.0036	0.0205	0.4290	0.4444	1.2007	0.0456	0.5173
10	0.0004	0.0015	0.0051	0.0003	0.0003	0.0026	0.0065	0.0012	0.0012	1.0782	0.1808
11	0.0024	0.0081	0.0287	0.0017	0.0018	0.0133	0.0369	0.0068	0.0069	0.0656	1.0409

Note: Table 3 indicates to which industry the numbers in the first column and first row refer to.

The Eurostat data also provides the 'as-planned' production levels ($\mathbf{x_i}$) for Italy for the 11 industries (see Table 6, column 2).

Table 6: As-planned production levels (x_i) for 2005 (million €)

Indus.	x_i Italy entire year	x_i Italy 1 day	x_i region north 1 day	x_i region centre 1 day	x_i region south 1 day	x_i region Sicily 1 day
1	44157	120.98	66.28	26.10	19.24	9.25
2	64665	177.17	97.07	38.21	28.17	13.55
3	101572	278.28	152.47	60.03	44.25	21.29
4	7826	21.44	11.75	4.63	3.41	1.64
5	10117	27.72	15.19	5.98	4.41	2.12
6	55122	151.02	82.74	32.57	24.01	11.55
7	69381	190.09	104.15	41.00	30.22	14.54
8	20522	56.23	30.81	12.13	8.94	4.30
9	21229	58.16	31.87	12.55	9.25	4.45
10	113020	309.65	169.66	66.79	49.23	23.69
11	853235	2337.63	1280.79	504.23	371.68	178.83

Note: Table 3 indicates to which industry the numbers in the first column refer to.

3.4. Assessment of inoperability and economic loss

Now that the matrix $\mathbf{B}^*$ and vector $\mathbf{x}$ have been obtained, the inoperability and economic losses for the eleven CI industries for a given demand perturbation resulting from the occurrence of a hazard can be determined. Due to the equilibrium assumption of the Leontief model, the economic losses are typically estimated on an annual basis. Hence, for smaller time resolutions, it is assumed that the losses are evenly distributed throughout the year (Anderson et al. 2007).[6] Therefore, 'as-planned' production in Italy for 24 hours is 1/365 of annual production, as mentioned in the third column of Table 6. Based on GDP data for Italy on the regional level, the as-planned production is disaggregated from the national to the regional level (see columns 3-6 in Table 6).[7]

The systems engineering model provides the IIM with the information to determine the demand side perturbation to the electricity industry for every region. This is done by approximating the surface above the recovery curves in Figure 2, by trapezoidal numerical integration. In this way, the recovery is implicitly taken account of in the analysis. As expected the values for $\mathbf{c}^*$ are higher for those regions that suffered longer from the outage (see Table 7, columns 2-5). Based on these values it is expected that in the region with the highest economic output (north) the impact of the outage is relatively low.

[6] Another assumption that arises from considering a relatively short period of time, is that all the considered industries in the analysis reach their steady-state values (see Table 5) within the considered period of time (one day in our case). In practice however, it may take longer for inoperabilities to cascade into other CI industries.

[7] The distribution of GDP in Italy in 2005 is as follows: north, 54.8%; centre, 21.6%; south, 15.9%; islands, 7.7% (source: Istat, the Italian National Bureau of Statistics).

Table 7: Regional demand-side perturbation vectors and inoperability vectors

Indus.	c* north	c* centre	c* south	c* Sicily	q north	q centre	q south	q Sicily
1	0.00	0.00	0.00	0.00	0.0052	0.0178	0.0209	0.0295
2	0.12	0.40	0.47	0.66	0.1375	0.4674	0.5496	0.7759
3	0.00	0.00	0.00	0.00	0.0014	0.0047	0.0055	0.0078
4	0.00	0.00	0.00	0.00	0.0039	0.0132	0.0155	0.0219
5	0.00	0.00	0.00	0.00	0.0011	0.0037	0.0044	0.0062
6	0.00	0.00	0.00	0.00	0.0026	0.0089	0.0105	0.0148
7	0.00	0.00	0.00	0.00	0.0020	0.0069	0.0081	0.0114
8	0.00	0.00	0.00	0.00	0.0012	0.0040	0.0047	0.0066
9	0.00	0.00	0.00	0.00	0.0015	0.0051	0.0059	0.0084
10	0.00	0.00	0.00	0.00	0.0002	0.0006	0.0007	0.0010
11	0.00	0.00	0.00	0.00	0.0010	0.0033	0.0038	0.0054

Note: Table 3 indicates to which industry the numbers in the first column refer to.

Using Equation 4, the inoperability vectors **q** are estimated. They are shown in Table 7. It can be observed that the perturbations to the electricity sector result in other sectors to be inoperable as well. Because of the dependency of the electricity sector within itself and with other industries, inoperability of this sector ultimately increases above the initial ($\mathbf{c}^*$) values. After applying Equation 5, the obtained economic losses per region are presented in Table 8.

Table 8: Economic loss (million €) for the selected CI industries as result of the 2003 power outage

Indus.	Italy	Region north	Region centre	Region south	Region Sicily
1	1.4854	0.3465	0.4639	0.4021	0.2729
2	57.1960	13.3430	17.8580	15.4820	10.5130
3	0.9006	0.2101	0.2812	0.2438	0.1656
4	0.1956	0.0456	0.0611	0.0529	0.0359
5	0.0714	0.0166	0.0223	0.0193	0.0131
6	0.9306	0.2171	0.2906	0.2519	0.1711
7	0.9031	0.2107	0.2820	0.2444	0.1660
8	0.1539	0.0359	0.0481	0.0417	0.0283
9	0.2031	0.0474	0.0634	0.0550	0.0373
10	0.1321	0.0308	0.0413	0.0358	0.0243
11	5.2488	1.2244	1.6389	1.4206	0.9649
Total	67.42	15.73	21.05	18.25	12.39

Note: Table 3 indicates to which industry the numbers in the first column refer to.

The analysis shows that, considering a system of 11 CI industries, economic losses for these industries are equal to €67.42 million for the whole nation of Italy. Applying the IIM to the system of 56 industries results in losses for the 11 CI industries of €81.79 million and for the

56 industries, a total economic loss of €123.17 million is found.[8] For a comparison, Simonsen (2005) mentions a total loss of $151 million for the 2003 power blackout in Italy, which is about €108 million. As expected, the IIM provides an overestimate (Rose and Liao, 2005). Because dynamic resilience is implicitly taken account of, the overestimate is small though.

Focusing on Table 8, the largest part of economic losses take place in the electricity, gas and water supply industry, which is expected as the perturbation influences directly on this industry. The second most-hit 'industry' is workforce, or the household sector. Because the household sector is made endogenous in the model it is regarded as one of the intermediate industries and its economic loss amounts €5.25 million. The interpretation of this loss is as follows: because other industries become inoperable to a certain degree, less labour inputs are needed, resulting in a reduction in value added through labour activities. Although the power outage lasted longest in the region Sicily, absolute economic losses are lowest in this region because of its relatively low economic output. See Appendix 1 for a presentation of the full results for Italy.

3.5. Applicability of the SE-IIM model

It is important that the IIM be applied to answer questions that are within the scope of input-output modelling. This scope is limited by the assumptions of the IIM. Crowther and Haimes (2005) state that as a result of the assumptions direct and indirect losses due to significant physical damage are not directly considered without the integration of engineering models.

The SE model is a simple tool of getting a rough picture of the phenomena that take place inside the considered system. The reduced number of nodes helps in getting a fast solution of the problem, though some information can be lost in the process. Right now, the model has not been sufficiently developed to analyse electricity infrastructure failure and recovery in other countries. We can to say however, that the current version can be used for analysing failure and recovery propagation of any potential failure to the Italian power grid.

One of the strengths of the IIM is its holistic character. It can be applied to a complete system of industries, representing the economy of a region, country, or set of countries to get a picture of the whole. Nevertheless, one can also zoom in into a subsystem of industries to get a (rough) picture of the economic impact of a hazard on a set of industries, like in this case

[8] These figures are shown in Appendix 1. Note that the increase in economic loss from €67.42 million to €81.79 million originates from the presence of more and stronger interdependencies because they are calculated in a larger system. The increase in economic loss from €81.79 million to €123.17 million originates from the presence of more industries (56 instead of 11 industries).

study. An approach that is only able to view a particular subsystem leads to a limited understanding of the problem, because generality is lost, which is undesirable. Next, the IIM offers a straightforward procedure to quickly obtain information on interdependencies in an economy. In addition, data availability is good. Eurostat offers I-O data for every EU Member State, which allows for an analysis of effects of infrastructure failure for every country in the EU.

4. CONCLUSIONS, LIMITATIONS, AND FURTHER RESEARCH

As shown in the previous section, the system-engineering model is able to predict the behaviour of the network for relatively large time scales (hours). Since the failure of the Italian grid happened at a smaller time scale (minutes), improvements should be performed in order to be able to use it for modelling of such phenomena. Moreover, the capability of the model to work with other types of CI's should be tested.

The IIM is a valuable tool for assessing economic losses for a system of industries. Its strength lies in its ability to narrow down the broad economic field to achieve usable results without losing generality. It has been shown, in a straightforward manner, how this tool can be used to analyse economic consequences of CI failure.

In addition to the strengths of the IIM, also several important limitations of the model must be addressed. First, sectors use inputs in fixed proportions. In other words, the model assumes fixed technical coefficients in $\mathbf{A}$ (the a_{ij}'s), and thus also the interdependencies in $\mathbf{A}^*$ (the a_{ij}^*'s) before, during and after the occurrence of a disaster are fixed. However, in real life a disaster is likely to change one or more elements of matrix $\mathbf{A}$ and thus also the $\mathbf{A}^*$ matrix. Setola et al. (2009) describe a novel approach, which is further developed in Oliva et al. (2011), to estimate IIM parameters whose size depends on the duration of inoperability. However, this methodology is time consuming and costly, especially for larger systems (like the 56×56 system used in this study). Second, the presence of constant returns to scale can be mentioned. Note that this follows from the first limitation: since the technical coefficients - which describe the relationships between a sectors output and its inputs - are fixed, the level of inputs increases (decreases) proportionally with the level of outputs. Third, $\mathbf{c}^*$ is demand based, so every supply-based reduction is treated like a forced reduction in demand. Fourth, the interdependencies matrix relies solely on information on exchanges of commodities between various interconnected sectors. It is assumed that these exchanges can act as proxies for real interdependencies among the industries. Fifth, and according to Crowther and Haimes

(2005), there are limits to the duration of the perturbation. Disturbances of too short duration will be easily overcome through short-term adaptation (resilience). Therefore, a disturbance must be long enough to take effect (at least a few hours), but short enough (at most a year) to avoid excessive substitutions translating into major changes in technical coefficients (the first mentioned limitation). Next, there are several damage types that are not valued. For example, there are start-up costs for some industries after the outage and goods and inputs may be lost when production processes stop. In addition, households loose the possibility to use their leisure time as a result of an outage, since many (if not all) leisure activities are electricity dependent. This lost leisure time is not valued in an IIM. Last, the I-O data from 2005 are used, while the power blackout analyzed occurred in 2003. Considering that interdependencies and national GDP do not change tremendously within 2 years time, this is not a major drawback.

The next step is to extend the SE-IIM model in various dimensions. Explicitly modelling recovery, taking into account resilience measures is one direction. Making the model spatially explicit by means of creating regional A* matrices is a second improvement. Another extension is to incorporate cross-border effects in the estimation thereby taking account of economic losses in neighbouring countries. In addition, more work on the validation of the model is desirable. Now, our result is compared with only one other loss estimate and preferably we present a range of outcomes.

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Appendix 1

Total use and economic losses for Italy (× million €) due to the 2003 power blackout

Industry	Total use 2005	Total use 1 day 2005	Economic loss 56 indus	Economic loss 11 indus
Agriculture, hunting and related service activities	44727	122.54	0.8845	
Forestry, logging and related service activities	455	1.25	0.0308	
Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing	2221	6.08	0.0467	
Other mining and quarrying	5767	15.80	0.1832	
Manufacture of food products and beverages	105101	287.95	1.9194	
Manufacture of tobacco products	1540	4.22	0.0543	
Manufacture of textiles	36268	99.36	0.4992	
Manufacture of wearing apparel; dressing and dyeing of fur	31239	85.59	0.4793	
Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear	27445	75.19	0.4113	
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	18014	49.35	0.3157	
Manufacture of pulp, paper and paper products	19350	53.01	0.6093	
Publishing, printing and reproduction of recorded media	26069	71.42	0.5681	
Manufacture of coke, refined petroleum products and nuclear fuels	44157	120.98	2.1270	1.4854
Manufacture of chemicals and chemical products	71012	194.55	2.2262	
Manufacture of rubber and plastic products	36983	101.32	0.8702	
Manufacture of other non-metallic mineral products	42812	117.29	0.8346	
Manufacture of basic metals	44527	121.99	1.2673	
Manufacture of fabricated metal products, except machinery and equipment	90476	247.88	1.9138	
Manufacture of machinery and equipment n.e.c.	108650	297.67	1.5730	
Manufacture of office machinery and computers	4449	12.19	0.1722	
Manufacture of electrical machinery and apparatus n.e.c.	35643	97.65	1.0779	
Manufacture of radio, television and communication equipment and apparatus	16323	44.72	0.3582	
Manufacture of medical, precision and optical instruments, watches and clocks	15761	43.18	0.1895	
Manufacture of motor vehicles, trailers and semi-trailers	41209	112.90	0.7607	
Manufacture of other transport equipment	19414	53.19	0.2563	
Manufacture of furniture; manufacturing n.e.c.	39797	109.03	0.5860	
Recycling	3280	8.99	0.0902	
Electricity, gas, steam and hot water supply	64665	177.17	58.2810	57.1960
Collection, purification and distribution of water	6686	18.32	0.3022	
Construction	184823	506.37	1.5449	
Sale, maintenance and repair of motor vehicles and motorcycles; retail sale services of automotive fuel	66025	180.89	1.3369	
Wholesale trade and commission trade, except of motor vehicles and motorcycles	166831	457.07	3.6794	
Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods	128371	351.70	2.2129	
Hotels and restaurants	99920	273.75	1.9472	
Land transport; transport via pipelines	101572	278.28	2.4668	0.9006
Water transport	7826	21.44	0.2562	0.1956
Air transport	10118	27.72	0.2493	0.0714
Supporting and auxiliary transport activities; activities of travel agencies	54138	148.32	1.1797	
Post and telecommunications	55122	151.02	1.7606	0.9306
Financial intermediation, except insurance and pension funding	69381	190.09	1.9764	0.9031
Insurance and pension funding, except compulsory social security	20522	56.23	0.3906	0.1539
Activities auxiliary to financial intermediat.	21230	58.16	0.4832	0.2031
Real estate activities	187109	512.63	3.4360	
Renting of machinery and equipment without operator and of personal and household goods	8853	24.25	0.2587	

Computer and related activities	43304	118.64	1.1627	
Research and development	11732	32.14	0.2570	
Other business activities	158380	433.92	3.7725	
Public administration and defence; compulsory social security	117459	321.80	0.0379	
Education	73448	201.23	0.3257	
Health and social work	113021	309.65	0.3327	0.1321
Sewage and refuse disposal, sanitation and similar activities	17194	47.11	0.6352	
Activities of membership organisation n.e.c.	5812	15.92	0.1242	
Recreational, cultural and sporting activities	34344	94.09	0.5512	
Other service activities	16888	46.27	0.2420	
Private households with employed persons	11955	32.75	0.1888	
Workforce	853236	2337.63	13.4696	*5.2488*
Total 11 industries			*81.79*	*67.42*
Total 59 industries			*123.17*	

Note: figures in italic are mentioned in the text. Values in the last column are all smaller than their corresponding values in the fourth column because of the presence of fewer interdependencies.