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DOI 10.1007/s11067-014-9259-1

Analysis of Critical Infrastructure Network Failure in the European Union: A Combined Systems Engineering and Economic Model

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Abstract Over the past few years, the European Commission has placed Critical Infrastructure Protection under the spotlight. Therefore, the Joint Research Centre is developing a tool to estimate the economic impact of Critical Infrastructure (CI) network failure, resulting from a hazard, on the regional or national level. This tool, which is presented in this study, is a combined Systems Engineering and Dynamic Inoperability Input–output model (SE-DIIM). The resilience of infrastructures and economic sectors, in terms of their ability to withstand and recover from disruptions, is included in the model. We discuss the model by analyzing the economic losses incurred in the 2003 Italian electricity network outage. The losses are estimated at both national and regional levels i.e. northern, central and southern parts of Italy and Sicily with a focus on 9 CI's. We estimate that the economic loss for the case study under consideration is between €46 million and €173 million. We conclude that the combination of the SE and the DIIM components provides a complete framework for assessing the economic impact of critical infrastructure network failure on the national or regional level taking account of resilience.

Keywords Critical infrastructure network failure · Systems engineering model · Dynamic inoperability input–output model · Static resilience · Dynamic resilience

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Published online: 14 September 2014

1 Introduction

The Joint Research Centre (JRC), among others, provides technical support to European policies in the domain of Critical Infrastructure Protection. These policies are part of the overall framework of European Programme for Critical Infrastructure Protection (EPCIP). The legislative tool of EPCIP is the Council Directive 2008/114/EC for the identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection. Its goal is to assess and address the needs for improving the protection of CI's. The relevant sectors and subsectors that are currently covered by the aforementioned Directive are depicted in Table 1.

The Directive mentions the economic effects of infrastructure failure as one of the criteria on which an infrastructures' criticalness is evaluated.[1] The objective of this paper is therefore to establish a methodology to assess those effects.

This methodology is grounded in a model which consists of two components: a Systems Engineering model and a Dynamic Inoperability Input–output model (SE-DIIM for short). The model first applies the systems engineering component to analyse performance degradation and recovery of a disrupted infrastructure network. Next, economic losses are estimated for a system of CI's and economic sectors using the DIIM component, which leverages information from the SE component. In both components, resilience is included in the analysis where we distinguish between static and dynamic resilience. These measures for resilience are adopted from Rose (2007; 2009) where static resilience refers to the ability of a system to maintain function when shocked and dynamic resilience concerns the speed of recovery of a system.[2] The relevance of the resilience concept for socio-economic systems was already pointed out by Reggiani et al. (2002).

The SE component is based on a modular technique which enables modelling interconnected infrastructures taking into account the functional interdependencies existing between them in a comprehensive way (Filippini and Silva 2014). Its key characteristics are that it is applicable at different scales of CI networks while it requires a limited amount of state variables, thus reducing the overall data needs. For our study, the SE component is applied to the Italian electricity infrastructure network being an interconnection of four major districts: Northern Italy, Central Italy, Southern Italy and Sicily. This enables us to build up a structured representation of 1) the gradual spread of the blackout event, 2) the service restoration process, which took place on different time scales due to the sudden nature of the accident and, 3) the stress level impacting the whole Italian electricity network.

The economic component (the DIIM) analyses cascading inoperability – a measure for the level of dysfunction of an infrastructure—that results from interdependencies within a system of infrastructures and economic sectors (Crowther and Haimes 2005).[3] The importance of the workforce (the household sector) in the context of hazard loss

[1] More details on the Directive can be found in http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:345:0075:0082:EN:PDF

[2] The challenge in improving the recovery speed of an infrastructure after a disaster is to maximize infrastructure performance within budgetary restrictions. This is actually a study in itself, as addressed by Matisziw et al. (2010).

[3] So where the SE component analyses failure and recovery *within* an infrastructure network in the present study, the DIIM component models the interaction *between* infrastructures.

Table 1 The Critical Infrastructures included 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	

estimation is emphasized several times in the literature (Santos and Haimes 2004; Ferrari et al. 2011). Workforce is therefore included in the DIIM and modelled as a CI sector. In order to include all main actors in an economy (businesses, households and the government) we also close the model with respect to government sales and purchases. In its application in the present study, the DIIM estimates the economic losses resulting from the electricity infrastructure network disruption in Italy in 2003, where cascading losses to other CI's and economic sectors are included in the estimation. The economic component of the model is chosen specifically for its universality and adaptability. Indeed Greenberg et al. (2012) claim that the Inoperability Input–output Model (IIM) is one of the ten most important accomplishments in risk analysis in the past 30 years.

The reason for applying an engineering model in tandem with an economic model is threefold. Firstly, the SE component captures with high accuracy the propagation and reduction of inoperability in one or more infrastructures. Consequently this specific information, which is generally absent in such detail as input data in DIIM applications (see Anderson et al. 2007 for example), is fed into the economic component. Secondly, with a DIIM it is assumed that interdependency levels between infrastructures and economic sectors can be approximated by the level of the monetary value of exchange of goods and services between them. However, especially during unstable states like electricity blackouts, functional interdependencies are likely to predominate (Oliva et al. 2011). As the SE component is able to model those functional interdependencies, its use is paramount in order to tune the DIIM for accurately assessing economic impact of CI disruptions. In some studies (Devogelaer and Gusbin 2004; De Nooij et al. 2007), it is assumed that for infrastructures which have a functional relationship, the transmission of a failure is total. This is another way for correcting the above mentioned deficiency of the DIIM but likely leads to an overestimation of the economic impact because it neglects the presence of resilience measures. Thirdly, the SE-DIIM satisfies the point made by Buldyrev et al. (2010) and Gao et al. (2012) that complex networks have been studied intensively, but research still focuses on the limited case of a single, non-interacting network. In the end, many real-world networks do interact with and depend on other networks.

Economic losses can be defined as stock damage or flow losses (business interruption losses). 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 direct or indirect nature. Direct effects are sustained 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 (indirect stock damage) or that are dependent on the initially hit sector through supply and demand relationships (indirect flow effects). Table 2 summarizes the different types of economic impact.

Input–output (I-O) models, and thus also our DIIM, ignore stock damages and only take into account direct and indirect flow losses. Including both stock damages and flow losses would result in double counting. The value of an asset, for example equipment pertaining to an infrastructure, is the discounted flow of net future returns from its operation. So suppose that a machine with a 1-year lifespan is destroyed, and not replaced for a year, then the economic loss is equal to either the value of a replacement machine with a 1-year lifespan or the discounted flow of not produced output for 1 year (Rose and Lim 2002).

In the next section, the theoretical framework of the SE and the DIIM components are described. In Section 3, an application of the model to the 2003 electricity blackout in Italy is discussed. The last section reports the conclusions.

2 Model Description

The SE-DIIM affords a certain level of abstraction in modelling which is still reasonable for obtaining a valid representation of the infrastructure and the dynamics of the event being considered. Previous work performed in JRC (Di Mauro et al. 2010), adopted the same systemic approach for CI network failure modeling and identified three layers of analysis: the micro level (links and nodes), the meso level (an infrastructure or economic sector) and the macro level (a set of infrastructures and sectors). All these layers are also covered with our proposed model. The micro-meso level corresponds to the engineering component (which is explained in Section 2.1) where sectors and infrastructures are described on the basis of nodes and links. In particular nodes represent assets (for example generators, loads, etc.) while links represent functional interdependencies (see Filippini and Silva 2014). The meso-macro level is represented by the DIIM modeling paradigm for dynamic inoperability, which we discuss in Section 2.2. The improvement provided by our model over the

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

previous infrastructure specific model is that it can be applied to a wide spectrum of CI networks and thus is more generally applicable.

2.1 Systems Engineering Component

In electrical power systems, a great variety of different dynamic processes take place. These dynamic phenomena have different physical origins and occur on different time scales. However, modelling all these phenomena is a cumbersome task that requires time consuming simulations and a very detailed knowledge of the electricity system at any moment and exceeds the scope of the present analysis. Relevant and adequate simplifications are often beneficial for analysing the system, as well as for obtaining results that are easy to understand and interpret. A commonly used approach for assessing CI failure is based on network concepts. Using this approach, a CI (for example, an electricity infrastructure network) is abstractly modelled as a network of nodes interconnected by links (Rigole and Deconinck 2006; Wilde and Warren 2008). The nodes are the model representation of the CI's assets (such as power stations, power plants, etc. in the case of the electrical system). The role of the nodes is to produce, store and/or to transform a specific type of resource, of limited availability, that characterises the CI. The transmission lines that connect the aforementioned units of the CI represent the links of the electricity network. The nodes (depicted with their suffixes in Fig. 1) can be a sub-network in their own right, with nodes and links (L_{ij}), where i is the source node and j the sink node.

Depending on the scope and goals of the modelling procedure, different levels of abstraction of the network elements can be afforded. The modeller is therefore free to decide on where to stop the detail level of the system's modelled structure. This networked way of visualising CI systems implies that the resulting model structure can capture the key features of the system i.e. the types of nodes present and the way they are connected.

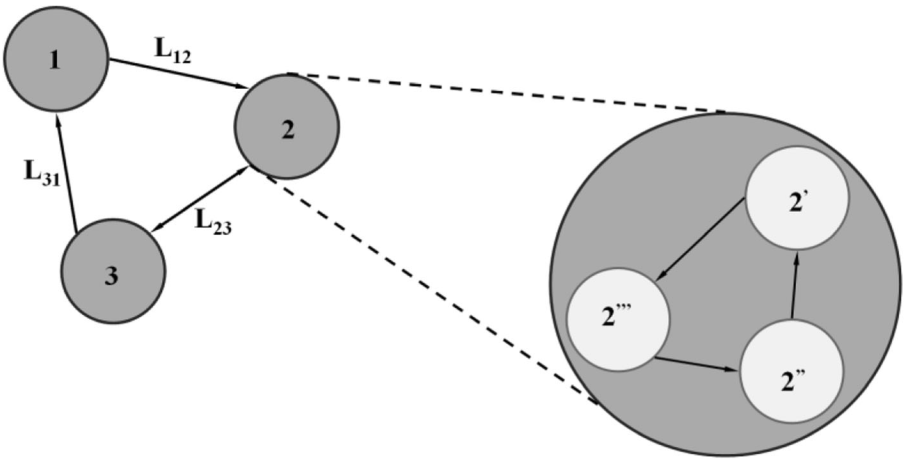

Fig. 1 Representation of a CI network. Each node may represent a sub-network.

With the SE component the behavior of the system is modeled by applying the conservation principle of the resources of the system. Based on this principle, a resource balance equation holds, which is written in general form in Eq. 1 (Bird et al. 2002):

$$R_{accumulation} = R_{in} - R_{out} + R_{generation} - R_{consumption} \tag{1}$$

Therein, $R_{accumulation}$ represents the accumulated resource, depending on both external resource exchanges and on possible inner resource generation and consumption processes. The conservation equation is versatile because, in our setup, it can be applied indifferently to the complete system or to each of the networks' nodes.

In this paper, we associate to a node i in the electricity network a simple internal dynamical model, consisting in a generic state of service variable $\varphi_i \in [0, 1]$, where 1 denotes full operability. We assume that the state of service of each node i, when exposed to a disruptive event generated by some other nodes of the network, can be described by 1) its static resilience, associated to the ability of node i to continue its operation despite being disrupted, ensuring a serviceable status, and 2) its dynamic resilience, being node i's ability to recover from disruptions to a serviceable status. The dynamic model representing the state drift of node i is described by Eq. 2.

$$\varphi_i(t) = e^{-f_i(t - T_{fi})}, \forall t \in [T_{fi}, \min(T_{ri}, T_{end})] \tag{2}$$

where $f_i \geq 0$ is the buffering capacity of node i, T_{fi} the starting point of the performance drift, T_{ri} is the starting time of the recovery process assuming that it exists and T_{end} is the considered time horizon. The use of an exponential drift model is in accordance with fault classification as reported in (Deckers and Jepsen 2003). Also the recovery process is modeled as an exponential drift as described in Eq. 3.

$$\varphi_i(t) = \varphi_i(T_{ri}) + (1 - \varphi_i(T_{ri}))\left(1 - e^{-r_i(t - T_{ri})}\right), \forall t \in [T_{ri}, T_{end}] \tag{3}$$

$T_{ri} \in [T_{fi}, T_{end}]$ is the normalized starting time of the recovery process, assuming that a recovery action takes place for node i.

2.2 Dynamic Inoperability Input–Output Component

The Dynamic Inoperability Input–output model (or DIIM) is an extension of the static Inoperability Input–output Model (or IIM) proposed by Santos and Haimes (2004) and linearly derived from Wassily Leontief's I-O model of the economy (Leontief 1951a, b). The DIIM is thus related to the principles of Input–output analysis. The DIIM used in the present study is slightly different from the standard version as presented in Haimes et al. (2005a; 2005b) and is provided in discrete-time form in Eq. 4.

$$q_i(t+1) = \max \begin{cases} p_i(t+1) \\ q_i(t) + k_{ii}\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \end{cases} \tag{4}$$

$q_i(t)$ is the inoperability of (infrastructure) sector i at time t expressed by the ratio of unrealized production (due to any cause whatsoever) with respect to the 'as-planned' production level of the (infrastructure) sector. Production inoperability $p_i(t)$ is similar to

$q_i(t)$ but describes inoperability of the production process of (infrastructure) sector i only due to a physical disruption in that process (Barker and Santos 2010). It is therefore exogenously determined and described by Eq. 5.

$$p_i(t) = e^{-l_{ii}t} p_i(0) \tag{5}$$

Dynamic resilience is included in the model by means of the sectoral resilience coefficient k_{ii} and the repair coefficient l_{ii}. The resilience coefficient of sector i describes the ability of sector i to recover following a disruptive event, and includes the extent to which the sector is interconnected with other potentially inoperable sectors (see Eq. 6). It is a function of the initial inoperability level at t=0, the desired inoperability level at the final time period T_i (usually set equal to 1 % in case of full recovery), the total number of time periods needed to achieve this desired inoperability level, and a correction for the degree of being dependent on other sectors. The repair coefficient of sector i describes the ability of the sector to recover production capability from an initial disruptive event, with no interdependent effects included in its calculation because it recovers autonomously as shown in Eq. 7 (Barker and Santos 2010).

In addition to a shock on the supply side, inoperability q_i can also be the result of a sudden drop in demand. Think of the decrease in demand for air transport after the 9/11 attacks for example. Therefore, the term $c_i^*(t)$, the demand-side perturbation of sector i at time t expressed in terms of relative degraded final demand is included in Eq. 4.

$$k_{ii} = \frac{1\mathrm{n}(q_i(0)/q_i(T_i))}{T_i}\left(\frac{1}{1-a_{ii}^*}\right) \tag{6}$$

$$l_{ii} = \frac{1\mathrm{n}(q_i(0)/q_i(T_i))}{T_i} \tag{7}$$

a_{ij}^* shows the contribution of a disrupted (infrastructure) sector i to the inoperability of sector j (Ali and Santos, 2012) and is derived from a Leontief coefficient, a_{ij}, and the production potential of industries i and j (x_i and x_j). The a_{ij}^*'s are stored in A^*, the normalized interdependency matrix as presented in Eq. 8. This matrix indicates the degree of coupling of the (infrastructure) sectors.

$$A^* = \begin{pmatrix} a_{11}\left(\frac{x_1}{x_1}\right) & \cdots & a_{1j}\left(\frac{x_j}{x_1}\right) & \cdots & a_{1n}\left(\frac{x_n}{x_1}\right) \\ \vdots & & \vdots & & \vdots \\ a_{i1}\left(\frac{x_1}{x_i}\right) & \cdots & a_{ij}\left(\frac{x_j}{x_i}\right) & \cdots & a_{in}\left(\frac{x_n}{x_i}\right) \\ \vdots & & \vdots & & \vdots \\ a_{n1}\left(\frac{x_1}{x_n}\right) & \cdots & a_{nj}\left(\frac{x_j}{x_n}\right) & \cdots & a_{nn}\left(\frac{x_n}{x_n}\right) \end{pmatrix} \tag{8}$$

Economic losses across all sectors at time t are expressed in Eq. 9 as a function of inoperability at time t and as-planned production output in that time period. The total economic loss, Q, can be found by means of Eq. 10, which sums the losses over all time periods. As-planned production output, $x(t)$, is assumed to be equal for every t.

$$Q(t) = diag(q(t))x(t) \tag{9}$$

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

$$Q = \sum_{t=0}^{T} Q(t) \tag{10}$$

3 Model Application

3.1 Case Study Description

The case study presented is the Italian power blackout that took place on September 28th, 2003 (also see Buldyrev et al. 2010). This blackout affected the whole country and about 45 million people had to withstand shorter or longer power shortages. Electricity was not supplied for a time interval ranging from 1.5 h in the northern part of Italy to 18 h in Sicily (Sforna and Delfanti 2006). The events on the evening of 28th September 2003 began at 03:01 a.m. Due to a sequence of power line tripping in the subsequent 25 min the Italian grid was separated from the UCTE (Union for the coordination of Transmission of Electricity), now known as European Network of Transmission System Operators for Electricity (ENTSO-E). At 03:28 a.m. a general blackout occurred across Italy.

3.2 Systems Engineering Component

Some studies (Rosato et al. 2007; Rocco et al. 2012) have modeled the Italian high-voltage electricity network (IHVETG) as an undirected graph of 127 nodes and 171 links, trying to assess the system vulnerability. Others used 310 nodes and 361 links (Rosato et al. 2011). For the purpose of our study, the Italian network is split into four sub-networks and consists of:

a) Northern Italy: Aosta Valley, Piedmont, Liguria. Lombardia, Friuli-Venezia Giulia, Trentino-Alto Adige and Veneto;
b) Central Italy: Emilia-Romagna, Tuscany, Umbria, Lazio, Marche, Abruzzo and Molise (excluding Sardinia that was already disconnected that night);
c) Southern Italy: Campania, Basilicata, Puglia and Calabria;
d) Sicily.

These four sub-networks will be considered as macro nodes of the national electricity infrastructure network. This simplification considerably reduces the size and complexity of the modelling problem. The connections of the IHVETG with the following countries are also considered: France, Switzerland, Austria, Slovenia and Greece.

The start of the event, i.e. t=0 in the applied modeling procedure, is assumed to coincide with the moment the outage began (3:01 a.m., 28th September 2003). According to the reports of the event, the cascading events leading to the separation of the North of Italy from Switzerland, France, Austria and Slovenia culminated at 3:26:24 and lead to a very fast propagation of the blackout from the North towards the South.

Compared to the fast dynamics of the blackout propagation stage, what is more interesting from the economic impact analysis perspective is the restoration stage, whose duration is considerably longer. Notably, the restoration actions started at 3:28 a.m. while the complete operability was reached at 9:40 p.m. (Berizzi 2004). This was done by means of a process wherein, approximately, the restart of the network component followed the same sequence as the blackout. The North region was the first one to be reconnected to the French and Slovenian grids, followed by the reconnection with the Centre and South regions. Additionally, the connection with Greece was restored. Sicily was the last region to be connected and restored, hence the restoration times vary.

The service restoration data are taken from GRTN (2004) and the conservation equation (Eq. **1**) is applied to each node. The application of the SE model leads to the results shown in Fig. 2a-d. The response of a CI network to an event that disrupts its service typically consists of two stages: the failure period and the recovery period. During the failure period operability is equal to zero. In the North region this period is absent because recovery starts immediately. On the contrary in Sicily, the failure period lasts until t=7. At t=7 the recovery period (where operability>0) starts until the level of service is fully restored. Our findings are in agreement with the data available from the UCTE (2004) for the North and Centre part of the Italian grid. The lack of reliable data for the Southern and Sicily regions did not allow any comparison between estimated and measured values for these regions.

3.3 Economic Component

Input–output data from the World Input–output Database (WIOD, see Dietzenbacher et al. 2013) for Italy for the year 2003 is used to analyse the effect of the perturbations in the electricity infrastructure network (as presented in Fig. 2) on its related CI's and

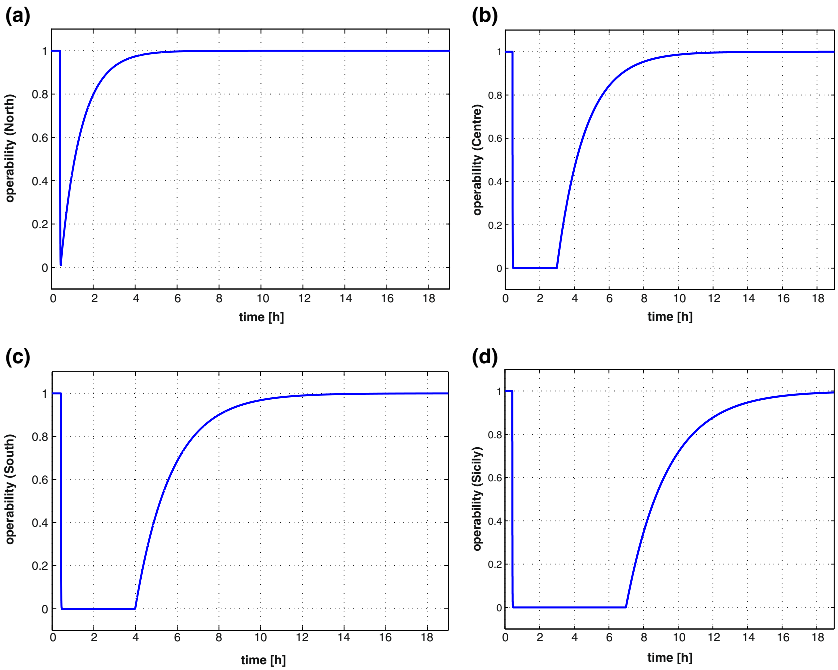

Fig. 2 **a** Output SE model region North **b** Output SE model region Centre **c** Output SE model region South **d** Output SE model region Sicily

Table 3 Selected Critical Infrastructures in WIOD I-O data

No.	WIOD sector	CI sector directive
1	Coke, refined petroleum and nuclear fuels	Energy
2	Electricity, gas, and water supply	
3	Inland transport	Transport
4	Water transport	
5	Air transport	
6	Post and telecommunications	
7	Financial intermediation	
8	Health and social work	
9	Workforce	

economic sectors in the four Italian regions. The data is of the industry-by-industry type and considers 37 sectors in total.[4] For our case study 9 out of the 37 industries are identified as potential Critical Infrastructures. Several of the WIOD sectors coincide with the industries as considered by the Directive in Table 1. They are presented in Table 3.

Table 4 presents interdependencies between the 9 CI's within the 37x37 interdependency (A^*) matrix for the national level. The entries in this table are used in Eq. 4 for transmission of inoperability between infrastructures and economic sectors (with the term $a^*_{ij}q_j$). Hence, an inoperability level of 50 % in infrastructure 2 results in a 6 % increase in inoperability in infrastructure 1 (0,5 * 0,12). Note that the self-dependency of infrastructure 2, to which the electricity infrastructure belongs, is artificially set equal to zero because the self-dependency of this infrastructure is already accounted for in the SE model.

3.3.1 Regionalization

Performing a spatially explicit analysis with respect to the considered regions requires the recalculation of A^*. After all, explicit intraregional interdependencies must be revealed because they are likely to differ from those on the national level. The regional interdependency coefficients are generally estimated using regional multipliers, which are constructed from measures of regional production compared to the national ones. In this study, these multipliers are formulated from location quotients, which are ratios that represent the relative production of a sector in a region compared to the nation (see Eq. 11). Equation 12 describes the application of location quotients in estimating intraregional interdependencies. If (infrastructure) sector i is less concentrated in the region than at national level ($lq_i^S<1$), it is seen as being less capable of satisfying regional demand with its output. However, if sector i is more highly concentrated in the region than at national level ($lq_i^S\geq 1$), it is assumed that the national input coefficients from sector i, a^*_{ij}, apply to the region, and the regional surplus produced by i will be 'exported' to the rest of the nation (Miller and Blair 2009).

[4] WIOD actually considers 35 economic sectors but because we close the model with respect to both the household and the government sector, there are 37 sectors in total.

Table 4 Interdependency matrix for the 9 selected infrastructures, Italy

Infra.	1	2	3	4	5	6	7	8	9
1	0.082	0.120	0.196	0.005	0.030	0.009	0.008	0.013	1.000
2	0.007	*0.000*	0.015	0.002	0.000	0.011	0.008	0.018	0.394
3	0.002	0.006	0.073	0.002	0.004	0.009	0.004	0.011	0.291
4	0.001	0.002	0.009	0.006	0.002	0.002	0.002	0.005	0.426
5	0.001	0.002	0.023	0.011	0.015	0.033	0.029	0.001	0.332
6	0.003	0.014	0.029	0.001	0.004	0.024	0.049	0.017	0.372
7	0.003	0.008	0.030	0.002	0.002	0.011	0.225	0.010	0.281
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.069	0.183
9	0.002	0.010	0.030	0.002	0.002	0.015	0.049	0.071	0.000

The numbers in column 1 and row 1 correspond with the CI numbers in Table 3

$$lq_i^s = \frac{x_i^s / x^s}{x_i^N / x^N} \tag{11}$$

$$a_{ij}^{*s} = \begin{cases} lq_i^s a_{ij}^*, & lq_i^s < 1, \\ a_{ij}^*, & lq_i^s > 1, \end{cases} \tag{12}$$

where lq_i^s is the proportion of demand for sector i in region s that is satisfied internally compared to other regions in the nation, x_i^s and x_i^N are the total production output of sector i in region s and nation N respectively, x^s and x^N are the total production output of all sectors in region s and nation N, respectively, a_{ij}^{*s} is the interdependency between infrastructures or sectors i and j in region s and a_{ij}^* is the interdependency between infrastructures or sectors i and j in in the nation.

The location quotients are based on national and regional employment data, which is a well-accepted proxy for output data. The procedure described above produces four interdependency matrices: A^{*North}, $A^{*Centre}$, A^{*South}, and $A^{*Sicily}$. The individual entries of the regional matrices have decreased in value or remained the same because each regional matrix is derived from the same national matrix and from location quotients that are strictly between 0 and 1. Intuitively, the values should decrease, because smaller regions are accounted for, and in this case, the degree of interconnectedness between sectors within the individual region decreases as well (Crowther and Haimes 2010).

3.3.2 Modelling Results

For the electricity network under consideration, the failure and recovery periods are produced by the SE model and shown in Fig. 2a-d. During the failure period, the CI is not able to start recovery. The concept of 'production inoperability', as described in Section 2, allows us to explicitly model the failure period. For the South region this

Table 5 Calculation of repair coefficients for electricity infrastructure

Region	Start recovery stage	Time needed	l_{ii}
North	hour 0	6 hours	ln(1/0.01)/6=0.767
Centre	hour 3	8 hours	ln(1/0.01)/8=0.576
South	hour 4	8 hours	ln(1/0.01)/8=0.576
Sicily	hour 7	11 hours	ln(1/0.01)/11=0.419

period lasts from t=0 until t=4, meaning that for this region $p(0)_{elec}=p(1)_{elec}=\ldots=p(4)_{elec}=0.776$.[5] The recovery period involves all the actions that eventually lead to the restoration of the service at the nominal operation levels at the end of this stage. For the South region this implies that recovery starts at t=5 and that full recovery is reached at t=12 so that $p(12)_{elec}=0.01$.[6]

The SE model thus provides the DIIM with regional initial (the moment at which recovery starts) production inoperability levels $p(0)^s_{elec}$, final recovery levels (full recovery), and the time needed for this full recovery which are then used as inputs for Eq. 7 to calculate the regional repair coefficients (l_{ii}) for the electricity sector (see Table 5). The other sectors and infrastructures are assumed to adjust their supply immediately relative to the new level of demand, corresponding to maximum resilience coefficients for $k_{ii}=1, j\neq i$ (Haimes et al. 2005a). Because there is no perturbation on the demand side, $c_i^*(t)=0$ for all t.

Table 6 provides the hourly 'as-planned' production levels for Italy (x_i) and its regions (x_i^s) for the 9 CI's. 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 'as-planned output' is evenly distributed throughout the year (Anderson et al. 2007). National 'as-planned production' is distributed over the regions on the basis of regional sectoral employment data.

Next, Eq. 4 is applied to each region in order to estimate inoperability levels. Inoperability propagates differently to other infrastructures and economic sectors due to regional differences in 1) interdependencies and 2) the duration of the electricity infrastructure failure and recovery period.

The economic losses per region (Q^s) are presented in Table 7. This table shows that total economic losses are equal to €46 million. About 36 % of these losses occur in the directly hit electricity, gas and water infrastructure sector. Also the CI 'workforce' suffers from significant losses, stressing the importance of including this CI in the model. Apparently, because infrastructure and economic sectors become inoperable, less labour inputs are needed, resulting in a reduction in value added through labour activities. Despite its long failure and recovery periods, Sicily suffered smaller absolute economic losses than the North region because of its relatively low economic output.

[5] The perturbation in the electricity sector ($p_{elec}=1$) is transformed into a perturbation for the aggregated 'electricity, gas *and* water supply' sector as considered in the national Input–output tables from the WIOD on the basis of Structural Business Statistics data from Eurostat. This data source tells us that in Italy the proportion of the production value of the electricity sector is 77,6 % of the production value of the aggregated sector 'electricity, gas and water supply'.

[6] Full recovery is set equal to $p_i(T_i)=0{,}01$ because one cannot divide by zero in Eq. 7.

Table 6 As-planned hourly production levels (x_i) for 2003 (million €)

Infra.	As-planned production, x_i					
	Italy entire year	*Italy 1 hour*	*North 1 hour*	*Centre 1 hour*	*South 1 hour*	*Sicily 1hour*
1	8952.6	1.02	0.67	0.19	0.08	0.08
2	43669.7	4.99	2.48	1.00	0.93	0.58
3	72842.3	8.32	4.11	1.87	1.60	0.74
4	5712.3	0.65	0.32	0.15	0.13	0.06
5	7917.3	0.90	0.45	0.20	0.17	0.08
6	41017.1	4.68	2.31	1.05	0.90	0.42
7	83074.2	9.48	5.35	2.28	1.26	0.60
8	79751.1	9.10	4.63	1.86	1.72	0.89
9	611776.2	69.84	35.95	14.59	13.19	6.11

The numbers in column 1 correspond with the CI numbers in Table 3

Further details regarding the losses for each infrastructure or sector are shown in Appendix 1.

As a comparison, Simonsen (2005) mentions a total loss of \$151 million for the 2003 power blackout in Italy, which is about €108 million at current exchange rates and significantly higher than our estimate. The likely explanation for this difference is that the interdependencies between the electricity infrastructure and other infrastructures and economic sectors are based on solely economic information, which is a limitation of the DIIM (Oliva et al. 2011). In addition, De Nooij and colleages (2007) argue that many production processes stop when electricity supply fails. Our economic loss estimate must therefore be regarded as a lower bound.

Table 7 Economic loss (million €)

CI/sector	Italy	North	Centre	South	Sicily
1	0.39	0.17	0.11	0.02	0.08
2	16.78	3.58	4.13	4.55	4.52
3	0.81	0.16	0.25	0.23	0.17
4	0.04	0.01	0.01	0.01	0.01
5	0.08	0.02	0.03	0.02	0.02
6	0.61	0.12	0.19	0.17	0.13
7	0.83	0.24	0.35	0.13	0.11
8	0.80	0.16	0.22	0.22	0.19
9	6.66	1.42	1.96	1.87	1.41
Total 37 sectors	46.46	12.19	12.62	11.54	10.11

The numbers in column 1 correspond with the CI numbers in Table 3

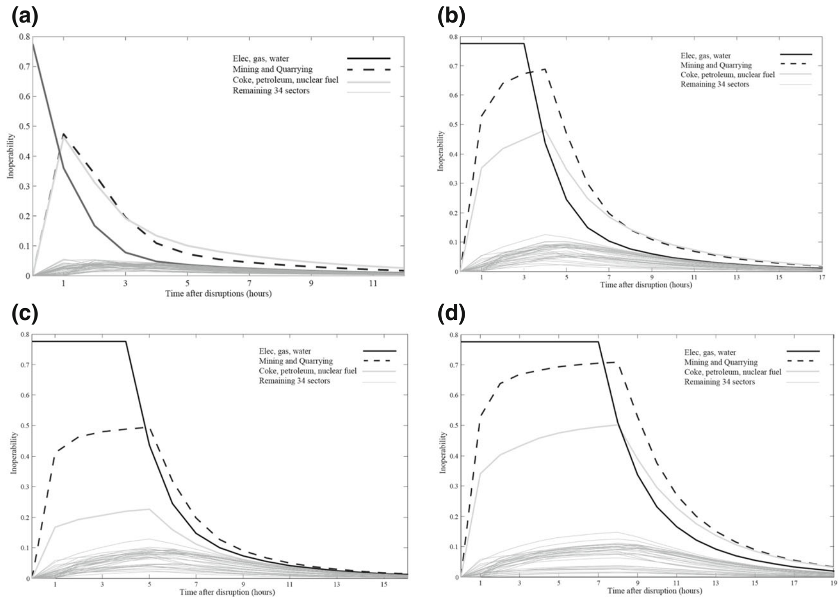

Fig. 3 **a** Inoperability DIIM region North **b**. Inoperability DIIM region Centre, **c** Inoperability DIIM region South, **d** Inoperability DIIM region Sicily

To put our estimate in a different perspective, in a sensitivity analysis we have multiplied the entries in the regional A^* matrices which correspond to the interdependencies between the electricity infrastructure and other infrastructures and economic sectors with a factor 5, rendering those latter sectors with higher inoperability levels. The inoperability levels in each region for this analysis are depicted in Fig. 3a-d. Especially the sector 'Mining and quarrying' and the CI 'Coke, refined petroleum and nuclear fuels' are sensitive for a perturbation in the electricity infrastructure network. Note that the remaining 34 (infrastructure) sectors are mentioned under one header in the legend. In the North region there is no failure period for the electricity infrastructure and recovery starts immediately. The total economic loss amounts up to €173 million in this case.

This loss can be expressed as the average damage per unit of electricity not supplied, the value of lost load, (or VoLL). Given that 177GWh was not supplied in the case study under consideration (UCTE 2004), the VoLL for the whole Italian society amounts to €0.98/kWh. Compared to values found in other studies (€8.56/kWh for the Netherlands (De Nooij et al. 2007) and €5.65/kWh for Belgium (Devogelaer and Gusbin 2004)), our VoLL estimate is rather low. The main reason is that both studies assume that in *all* economic sectors *all* production and leisure time is lost during an electricity supply interruption.[7] Considering that in practise resilience measures[8] may be present in several or maybe all (infrastructure) sectors, their VoLL estimates are likely to be upper bound values.

[7] In our study. this is similar to assuming that inoperability in all industrial sectors, the household sector and the government sector is equal to 1 during the failure period.

[8] Inventories or network redundancies for example.

4 Conclusion

In this study a Systems Engineering (SE) model has been coupled with a Dynamic Inoperability Input–output Model (DIIM) in order to create a modelling tool to support European policies on Critical Infrastructure Protection. In both model components resilience of infrastructure networks and economic sectors are included. The SE component accounts for both the buffering capacity of network nodes (static resilience) and the recovery speed (dynamic resilience) which determines the time needed to go back to full operability, while the DIIM component solely focuses on the latter resilience type.

The goal of the SE component of the model is to provide the DIIM component with reliable and detailed inputs regarding the initial shock to an infrastructure network, which is in this case the Italian electricity network failure of 2003. The next step is to extend the applicability of the SE component to more infrastructures. Abrell and Weigt (2012) for example present a general framework to combine energy markets, including detailed network characteristics. Furthermore, the modular set up allows the use of different SE components for assessing interdependencies and infrastructure inoperability, allowing for an even more accurate estimation of the economic impact. An advantage of the DIIM as proposed in this study, is that it is able to explicitly model a failure and a recovery stage after a disruption has taken place instead of assuming that recovery starts immediately like most DIIM applications do (see for example Haimes et al. 2005b or Lian and Haimes 2006). In addition, the economic component is supported by data from the World Input–output Database (WIOD) which offers a set of I-O tables for all EU countries. This is an advantage as the model presented must be applicable to all EU Member States.

For a correct interpretation of the results, several limitations of the DIIM must be addressed. First, economic and infrastructure sectors use inputs in fixed proportions (Miller and Blair 2009). In other words, the interdependencies in the matrix A^* (the a_{ij}^*'s) before, during and after the occurrence of a hazard are assumed to remain fixed. Second, 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. Third, and according to Crowther and Haimes (2005), there are limits to the duration of the failure period that can be modelled. Disturbances of too short a duration will be easily overcome through short-term adaptation. Therefore, a disturbance must take place long enough to produce effects (at least a few hours as in the case study considered), but short enough (at most several months) to avoid excessive substitutions translating into major changes in interdependencies. Last, several damage types 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.

Considering that our goal is to develop a model which includes resilience and is generally applicable (to many types of infrastructures, hazards, EU countries), the SE-DIIM is an appropriate tool. Future modelling efforts are needed however to reduce the mentioned deficiencies. How to improve the resilience of infrastructures is another logical next research direction. Du and Peeta (2014) offer an attractive model here by identifying those pre-disaster network link investment decisions which result in the best post-disaster (disrupted) network performance under different disaster scenario's.

Acknowledgments We would like to thank two anonymous referees for their valuable comments. This work is supported by the Annual Work Programme 2010 and Annual Work Programme 2011 for the specific programme on the "Prevention and fight against crime" which is financed by Directorate General Home Affairs of the European Commission. The authors would like to express their gratitude for this support.

Appendix

Table 8 Total use and economic losses for Italy due to the 2003 power blackout

Economic sector/CI	x_i 2003 (million €)	x_i 1 hour 2003 (million €)	Q_i 37 sectors (million €)
Agriculture, hunting, forestry and fishing	39990.2	4.57	0,47
Mining and quarrying	6722.4	0.77	0,46
Food, beverages and tobacco	80613.6	9.20	0,66
Textiles and textile products	54600.3	6.23	0,26
Leather, leather and footwear	22791.3	2.60	0,13
Wood and products of wood and cork	14015.6	1.60	0,07
Pulp, paper, paper, printing and publishing	33871.1	3.87	0,24
Coke, refined petroleum and nuclear fuel	8952.6	1.02	0,39
Chemicals and chemical products	46812.2	5.34	0,27
Rubber and plastics	25926.4	2.96	0,15
Other non-metallic mineral	31879.8	3.64	0,30
Basic metals and fabricated metal	87268.8	9.96	0,38
Machinery, nec	74550.9	8.51	0,20
Electrical and optical equipment	49027.5	5.60	0,22
Transport equipment	40621.7	4.64	0,10
Manufacturing, nec; recycling	30364.3	3.47	0,14
Electricity, gas and water supply	43669.7	4.99	16,78
Construction	131346.9	14.99	1,08
Sale, maintenance and repair of motor vehicles and motorcycles; retail sale of fuel	46160.3	5.27	0,51
Wholesale trade and commission trade, except of motor vehicles and motorcycles	127763.3	14.58	1,30
Retail trade, except of motor vehicles and motorcycles; repair of household goods	100941.5	11.52	1,03
Hotels and restaurants	76464.2	8.73	0,81
Inland transport	72842.3	8.32	0,81
Water transport	5712.3	0.65	0,04
Air transport	7917.3	0.90	0,08
Other supporting and auxiliary transport activities; activities of travel agencies	40493.4	4.62	0,40
Post and telecommunications	41017.1	4.68	0,61
Financial intermediation	83074.2	9.48	0,83
Real estate activities	142648.8	16.28	1,38
Renting of M&Eq and other business activities	167952.6	19.17	1,66

Table 8 (continued)

Economic sector/CI	x_i 2003 (million €)	x_i 1 hour 2003 (million €)	Q_i 37 sectors (million €)
Public admin and defence; compulsory social security	89028.1	10.16	0,80
Education	60449.2	6.90	0,70
Health and social work	79751.1	9.10	0,80
Other community, social and personal services	57916.1	6.61	0,73
Private households with employed persons	9066.2	1.03	0,10
Households	611776.2	69.84	6,66
Government	292960.3	33.00	2,15
Total 9 industries			*27.00*
Total 37 industries			*46.46*

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