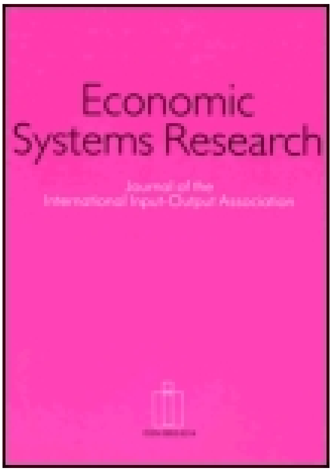


Economic Systems Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/cesr20

ANALYSING CRITICAL INFRASTRUCTURE FAILURE WITH A RESILIENCE INOPERABILITY INPUT-OUTPUT MODEL

Olaf Jonkeren[a] & Georgios Giannopoulos[a]
[a] European Commission, Joint Research Centre (JRC), Institute for the Protection and Security of the Citizen, Ispra, Italy
Published online: 23 Jan 2014.

To cite this article: Olaf Jonkeren & Georgios Giannopoulos (2014) ANALYSING CRITICAL INFRASTRUCTURE FAILURE WITH A RESILIENCE INOPERABILITY INPUT-OUTPUT MODEL, Economic Systems Research, 26:1, 39-59, DOI: 10.1080/09535314.2013.872604

To link to this article: http://dx.doi.org/10.1080/09535314.2013.872604

Economic Systems Research, 2014
Vol. 26, No. 1, 39–59, http://dx.doi.org/10.1080/09535314.2013.872604

ANALYSING CRITICAL INFRASTRUCTURE FAILURE WITH A RESILIENCE INOPERABILITY INPUT–OUTPUT MODEL

OLAF JONKEREN[*,†] and GEORGIOS GIANNOPOULOS

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

(*Received 28 August 2013; accepted 3 December 2013*)

Over the past few years much effort has been made in modelling economic losses resulting from critical infrastructure failure. It has appeared that including resilience measures in the modelling approach, which may mute the losses considerably, is a challenging task. At the same time it is necessary because it prevents the modeller from generating overestimates. This study presents two directions to improve the modelling of (economic) resilience for which the state-of-the art with respect to dynamic inoperability input–output modelling is taken as a starting point. Firstly, the new model allows for a different recovery path than the traditionally assumed 'concave up decreasing curve' describes for a disrupted infrastructure or economic sector in the aftermath of a disaster. In this paper, we explain how the recovery path may depend on the type of disaster. Secondly, the model refines the aspect of 'inventory' as a resilience measure. Inventory is interpreted in a broad sense here: it can be any resilience measures which enable an infrastructure or economic sector to continue its supply despite being disrupted. The model is applied to both a simple two-sector illustrative example and a severe winter storm scenario in Europe using economic data from the World Input–Output Database to show its practical usefulness.

Keywords: Inoperability input–output model; Economic resilience; Critical infrastructure; Recovery; Inventory

1. INTRODUCTION

Within the framework of the European Programme for Critical Infrastructure Protection (EPCIP), the Joint Research Centre (JRC) is developing models and tools for analysing economic losses resulting from infrastructure failure. The legislative instrument of EPCIP is Council Directive 2008/114/EC (European Council, 2008). The goal of the Directive is to identify Critical Infrastructures (CIs) of European dimension and consequently assess and address the need for improving their protection against any types of hazard. In the Directive a 'European Critical Infrastructure' is defined as

> an asset, system or part thereof located in Member States which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact on at least two Member States.

The infrastructures which are considered to be potentially critical can be found in Table 1.

*Corresponding author. E-mail: olaf.jonkeren@pbl.nl
†The work done by Olaf Jonkeren was conducted during his presence at the JRC. He is currently working at PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands.

TABLE 1. The CIs 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	

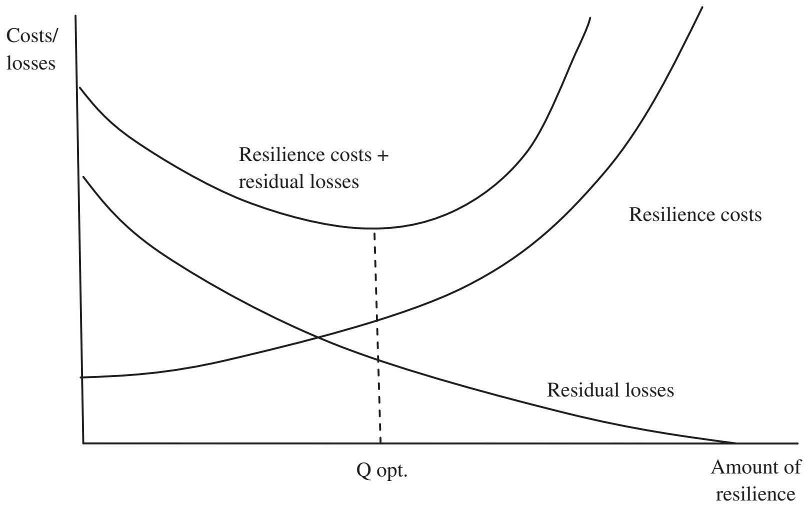
Source: European Council (2008).

To support the Directive we have developed an inoperability input–output model (IIM) which includes economic resilience. It will serve as a tool for the assessment of the size of the economic impact of CI failure and is called the 'Resilience IIM'.

The IIM (Santos and Haimes, 2004) has received significant attention in the literature. Greenberg et al. (2012), claim that the IIM is one of the 10 most important accomplishments in risk analysis in the past 30 years. Nevertheless, it has also been criticized for its limitations (Kujawski, 2006). Inoperability can be interpreted as the relative degradation of an infrastructure's or sector's capacity to deliver its intended output due to internal failures or external perturbations (Haimes et al., 2005a). One of the limitations of the IIM is the inability to model the effect of resilience measures on the output metrics 'inoperability' and 'economic loss'. Therefore, Haimes et al. (2005a; 2005b) have extended the model with the ability to model the speed of recovery of an economic sector, which gave rise to the dynamic IIM (DIIM). More recently, Barker and Santos (2010a; 2010b) have added another resilience dimension, namely inventory, which enables the DIIM to model delay in the onset of inoperability. This paper takes the Inventory DIIM as a starting point. The goal is to expand and improve the modelling of economic resilience in an IIM context and to show the value of these improvements using an illustrative example and a case study.

Economic resilience focuses on the flow of goods and services (economic output) rather than the stock of assets. Because an IIM analyses changes in such output due to some disturbance, it is considered suitable to include effects of economic resilience measures. Rose (2007; 2009) introduced two types of economic resilience: static and dynamic. Static economic resilience is the ability of an entity or system to maintain function when shocked. The substitution of inputs is an example here. Dynamic economic resilience is the speed at which an entity or system recovers from a shock to achieve a desired state. Recovery is achieved by repair and reconstruction of the capital stock. Although considered suitable, it is acknowledged by the authors that the capability of the DIIM to model resilience has its limitations. The price mechanism, for example, can be considered as an inherent resilience measure which automatically adjusts new levels of demand and supply in a post-disaster period. This way, goods and services are redirected in order to arrange their highest-value use (Rose, 2007). Our model does not account for price changes but is only able to analyse

FIGURE 1. Resilience costs and residual losses vs. the level of infrastructure resilience (Koetse and Rietveld, 2012).



changes in produced quantities.[1] We can therefore only speak about economic losses and not of welfare losses.

The present study focuses on two contributions regarding the modelling of economic resilience with a DIIM. Firstly, the model allows for a different recovery path than the traditionally assumed concave up decreasing function. This function assumes that recovery takes place relatively quickly in the first few time periods after a disaster but then slows down as time continues. In the current study, we argue why in some cases such a recovery path is less realistic and an alternative recovery path is proposed. Secondly, the role of inventory as a resilience measure (in the form of finished goods) is discussed in this study. Barker and Santos (2010a) have introduced the aspect of inventory in DIIM modelling as a means to delay the effect of disruptions in production processes only. In our model, inventory can be used to compensate for both: production losses due to physical production disruptions and disruptions in the supply of inputs.

Knowledge of economic losses following from infrastructure failure is required to responsibly invest in resilience measures. After all, the potential benefit of taking resilience measures is equal to the decrease in economic loss resulting from those measures. The relation between economic losses, resilience costs and the amount of investment in resilience measures for a given probability of occurrence of a disaster is presented in Figure 1. Because the most cost-effective investments with the highest benefits are assumed to take place first, marginal infrastructure resilience costs increase and marginal benefits decrease with the level of investment in resilience. The total of resilience costs and residual losses are minimal where the marginal costs of this total cost curve with respect to the level of infrastructure resilience are equal to zero. This is the case where the level of resilience is at its optimum (Q opt.). The model presented in this paper may help to find this optimum.

[1] See Rose and Liao (2005) who employed a CGE model which does include the price mechanism as a resilience measure.

The evolution of the IIM from a simple static version through to the Inventory DIIM is described in detail in the next section. Section 3 explains how the Inventory DIIM is refined on the economic resilience aspect, resulting in the Resilience IIM. The functioning of this model is illustrated in Section 4 using a simple two-sector example. Next, in Section 5 the model is applied to a case study for infrastructure failure in the European Union. Finally, Section 6 provides the conclusions of the study.

2. INOPERABILITY INPUT–OUTPUT MODELLING

The IIM, which was proposed by Santos and Haimes (2004), can be linearly derived from Wassily Leontief's input–output (I–O) model of the economy (Leontief, 1951a; 1951b). It was extended by Haimes et al. (2005a; 2005b) by adding the ability to recover from disruptive events, which changed the static IIM into a dynamic one (the DIIM). This recovery aspect coincides with the previously discussed 'dynamic economic resilience' concept. Subsequently, Barker and Santos (2010a) introduced the Inventory DIIM which has the ability to model effects of resilience measures that delay the onset of inoperability of an infrastructure or economic sector because it has access to some sort of inventory. Inventory can be represented by finished goods or some other method to maintain a sector's ability to provide goods or services to other infrastructures, sectors and final consumers while it is in a disrupted state. For example, inventory in the oil and gas sector could include excess stored gasoline ready for use, and in the electric power sector backup generators could provide some amount of total output to be maintained (Barker and Santos, 2010a). Such inventory can be regarded as a measure within the context of the earlier mentioned 'static economic resilience' concept. The Inventory DIIM as presented in Barker and Santos (2010a) can be found in Equation 1. The variables are explained below.

$$q_i(t+1) = \begin{cases} q_i(t) + k_{ii}\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \\ \quad \text{if } s_i(t+1) \geq p_i(t+1)x_i(t+1), \\ \max\begin{cases} p_i(t+1) - \dfrac{s_i(t+1)}{x_i(t+1)} \\ q_i(t) + k_{ii}\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \end{cases} \\ \quad \text{if } 0 < s_i(t+1) < p_i(t+1)x_i(t+1), \\ \max\begin{cases} p_i(t+1) \\ q_i(t) + k_{ii}\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \end{cases} \\ \quad \text{if } s_i(t+1) = 0, s_i(t) > 0, \\ q_i(t) + k_{ii}\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \\ \quad \text{if } s_i(t+1) = s_i(t) = 0. \end{cases} \quad (1)$$

In the above formulations, $q_i(t)$ is the inoperability of sector i at the end of time t expressed by the ratio of unrealized production with respect to the 'as-planned' production level of the sector. Production inoperability $p_i(t)$ is similar to $q_i(t)$ but describes inoperability of the production process of sector i at the end of time t due only to a physical disruption of that process.[2] The term $s_i(t)$ is the inventory level and it quantifies the amount of finished goods inventory in sector i remaining at the end of time t. Note that $q_i(0) = p_i(0)$ if no inventory is in place. The term $x_i(t)$ describes the total output anticipated to be produced by sector i between the end of time $t-1$ and the end of time t. Finally, k_{ii} is the sectoral recovery coefficient which has a value between 0 and 1 (Haimes et al., 2005a).[3] It indicates how fast sector i recovers from sector inoperability and is a function of the initial inoperability level at $t = 0$, the desired inoperability level in the final time period f_i (usually set equal to 1% in case of full recovery) and the total number of time periods needed to achieve this desired inoperability level (see Equation 2). The repair coefficient $\tilde{k}_{ii}$ is used to determine the speed with which a sector recovers from production inoperability.[4] The calculation of $\tilde{k}_{ii}$ is defined as presented in Barker and Santos (2010a) in Equation 3. a^*_{ij} shows the contribution of a disrupted sector i to the inoperability of sector j (Ali and Santos, 2012). The a^*_{ij}s are stored in $\mathbf{A}^*$, the normalized interdependency matrix that indicates the degree of coupling of the sectors. Finally, $c^*_i(t)$ is the demand-side perturbation of sector i at time t expressed in terms of relative degraded final demand.

$$k_{ii} = \frac{\ln(q_i(0)/q_i(f_i))}{f_i}\left(\frac{1}{1-a^*_{ii}}\right), \tag{2}$$

$$\tilde{k}_{ii} = \frac{\ln(p_i(0)/p_i(f_i))}{f_i}. \tag{3}$$

Production inoperability is calculated as in Equation 4 where $p_i(0)$ is the initial production inoperability experienced by sector i. Recovery is assumed to follow a concave up decreasing recovery path.

$$p_i(t) = e^{-\tilde{k}_{ii}t} p_i(0). \tag{4}$$

In order to be able to use Equation 1, initial sector inoperability must be determined. If there is enough inventory available to compensate for the output reduction caused by the initial production inoperability, defined as $p_i(0)x_i(0)$, then $q_i(0) = 0$. All possible initial inventory scenarios are described in Equation 5.

$$q_i(0) = \begin{cases} 0 & s_i(0) \geq p_i(0)x_i(0), \\ p_i(0)\left(1 - \dfrac{s_i(0)}{p_i(0)x_i(0)}\right) & 0 < s_i(0) < p_i(0)x_i(0)\ , \\ p_i(0) & s_i(0) = 0. \end{cases} \tag{5}$$

[2] Contrary to production inoperability, sector inoperability may be caused by something other than a physical disruption of the production process, a lack of inputs for example.

[3] The term 'recovery coefficient matrix' is used here instead of the commonly used term 'resilience coefficient matrix' (as in for example Akhtar and Santos, 2013) because economic resilience comprises more than recovery speed only, as explained.

[4] Note that the formula for $\tilde{k}_{ii}$ does not need the correction for the level of self-dependency of the industry because the repair speed is independent of any inoperability experienced in interconnected sectors.

Another aspect of the Inventory DIIM is the updating of inventory in every time period. Inventory depletes when it is used to compensate for production inoperability (see Equation 6).

$$s_i(t+1) = \max \begin{cases} s_i(t) - p_i(t)x_i(t), \\ 0. \end{cases} \tag{6}$$

Finally, economic losses across all sectors at time t are expressed in Equation 7 as a function of inoperability at time t and as-planned production output in that time period. The total economic loss, $\mathbf{L}$, can consequently be found by summing the losses over all time periods using Equation 8. As-planned production output, $\mathbf{x}(t)$, is assumed to be equal for every t.

$$\mathbf{l}(t) = \hat{q}(t)\mathbf{x}(t), \tag{7}$$

$$\mathbf{L} = \sum_{t=0}^{f} \mathbf{l}(t). \tag{8}$$

3. NEW METHODOLOGICAL CONSIDERATIONS

In this section, several directions for extending the Inventory DIIM are proposed and the theoretical implications of these extensions are explained.

3.1. A Different Recovery Path

In the Inventory DIIM, the ability of an infrastructure or economic sector i to recover following a disruptive event is determined by its recovery coefficient k_{ii}. If k_{ii} is found to be 0.2, for example, this implies that every time period inoperability is reduced by 20%. The resulting graph which visualizes the recovery path for a sector i which is confronted with an initial inoperability of $q_i(0) = 0.50$ is shown in Figure 2. This figure assumes that the recovery speed of industry i is high in the first few time periods after the disaster has occurred and then slows down. However, post-disaster situations can often be characterized as chaotic. Emergency and repair activities may be hampered and logistics are often complex. This implies slow recovery in the immediate post-disaster period, especially for those industries that are directly affected by the disaster because they are suffering from capital stock damage. In addition, finishing some first repair works may accelerate others.

For example, for a particular directly damaged infrastructure sector, which consists of a network of links and nodes, the restoration of one damaged link or node may accelerate the repair of others because they become better accessible. If such a situation applies, the assumed concave *up* decreasing recovery path can be relaxed. It may be more likely for directly impacted sectors that recovery follows a concave *down* decreasing path as depicted in Figure 3. For indirectly affected sectors, a concave *up* decreasing recovery path is likely because sector assets are still intact and recovery can thus be initiated relatively quickly.

We find the concave down decreasing recovery path for infrastructure or sector i with Equation 9.

$$p_i(t) = p_i(0)(1 + \mathrm{e}^{-\tilde{k}_{ii} f_i} - \mathrm{e}^{\tilde{k}_{ii}(t - f_i)}). \tag{9}$$

FIGURE 2. Classical concave up decreasing recovery path for a sector or infrastructure i in DIIM.

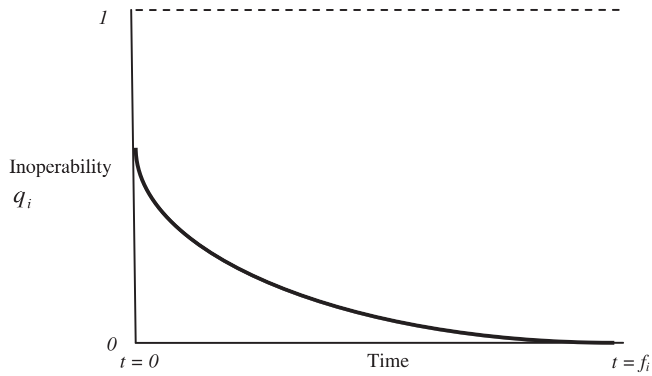
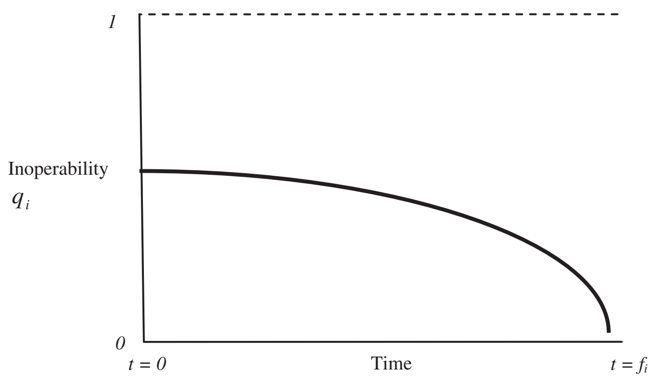


FIGURE 3. Concave down decreasing recovery path for a sector or infrastructure i.



3.2. Inventory as Compensation for Sector Inoperability

Intuitively, finished goods inventory depletes as it is used to compensate for production inoperability, $p_i(t)$ (Barker and Santos, 2010a). This process can be found in Equation 6. However, inventory may also be used to compensate for sector inoperability, $q_i(t)$, which can be caused by either production inoperability *or* inoperability received from other infrastructures and economic sectors. In this latter case $s_i(t)$ and $q_i(t)$ are dependent on each other. Therefore, depending on the inventory and inoperability situation at the beginning of a particular time period t, s_i and q_i might need to be calculated more than once within one time period. Table 2 provides an intuitive overview of this procedure.

Using this approach, inventory serves as a buffer for sector inoperability, irrespective of its cause (i.e. production inoperability or propagated inoperability from other sectors).

3.3. The Resilience IIM

Based on the refinements of the Inventory DIIM explained in Sections 3.1 and 3.2, the Resilience IIM in discrete form is implemented in Matlab and presented in Equation 10a

TABLE 2. Calculation of inoperability and inventory within one time period.

Step	Calculation
A	Calculate inoperability $q_i(t+1)$ on the basis of $q_i(t), p_i(t+1)$ and the availability of $s_i(t)$ to compensate for $p_i(t+1)$
B	Update inventory on the basis of what is necessary to cover lost production caused by $q_i(t+1)$ or $p_i(t+1)$ from step A
C	Update $q_i(t+1)$ to the extent to which $s_i(t)$ was able to compensate the $q_i(t+1)$ from step A
D	Transfer the remaining inventory to the next time period

and 10b and Equation 11a and 11b.[5] Equation 10a and 10b relates to the calculation of sector inoperability at the beginning ($q_i(t+1)$) and at the end ($\tilde{q}_i(t+1)$) of time period $t+1$. Equation 11a and 11b describes inventory at the beginning and at the end of time period $t+1$, which is represented by $s_i(t+1)$ and $\tilde{s}_i(t+1)$, respectively. At the start of a particular time $t+1$, sector inoperability is calculated depending on one of the (inventory) scenarios (1, 2 or 3) using Equation 10a, in which inventory can only be used to compensate for production inoperability.[6] Next, in Equation 11a, the inventory $s_i(t+1)$ that was present at the beginning of $t+1$ is updated on the basis of the amount necessary to compensate for the loss of as-planned output due to inoperability, resulting in the amount of inventory present at the end of time period $t+1, \tilde{s}_i(t+1)$. Then, using Equation 10b, and depending on the inventory situation, sector inoperability calculated with Equation 10a is updated resulting in the level of sector inoperability of sector i at the end of time period $t+1, \tilde{q}_i(t+1)$. Contrary to Equation 10a, in Equation 10b the inventory $s_i(t+1)$ present at the beginning of $t+1$ can be used to compensate for sector inoperability. Last, the amount of inventory at the end of $t+1$ is transferred to the next time period $t+2$ by using Equation 11b.

$$q_i(t+1) = \begin{cases} 1: q_i(t) + k_{ii}(t)\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \\ \quad \text{if } s_i(t+1) \geq p_i(t+1)x_i(t+1), \\ 2: \max\begin{cases} p_i(t+1) \\ q_i(t) + k_{ii}(t)\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \end{cases} \\ \quad \text{if } s_i(t+1) = 0 \\ 3: \max\begin{cases} p_i(t+1) - \dfrac{s_i(t+1)}{x_i(t+1)} \\ q_i(t) + k_{ii}(t)\left[c_i^*(t) - q_i(t) + \sum_{j=1}^{n} a_{ij}^* q_j(t)\right] \end{cases} \\ \quad \text{if } 0 < s_i(t+1) < p_i(t+1)x_i(t+1). \end{cases} \tag{10a}$$

[5] The initial conditions are determined by Equation 5.
[6] The scenario (1, 2 or 3) which applies to a certain infrastructure or sector i at time t in Equation 10a determines the relevant scenario in Equations 11a and 10b.

$$\tilde{s}_i(t+1) = \begin{cases} 1 : \max \begin{cases} 0, \\ \min \begin{cases} s_i(t+1) - p_i(t+1)x_i(t+1), \\ s_i(t+1) - q_i(t+1)x_i(t+1), \end{cases} \end{cases} \\ 2 : s_i(t+1), \\ 3 : \max \begin{cases} 0, \\ \min \begin{cases} s_i(t+1) - p_i(t+1)x_i(t+1), \\ s_i(t+1) - q_i(t+1)x_i(t+1). \end{cases} \end{cases} \end{cases} \tag{11a}$$

$$\tilde{q}_i(t+1) = \begin{cases} 1 : \begin{cases} 0 & \text{if } s_i(t+1) \geq q_i(t+1)x_i(t+1), \\ q_i(t+1) & \text{if } s_i(t+1) = 0, \\ q_i(t+1) - \dfrac{s_i(t+1)}{x_i(t+1)} & \text{if } 0 < s_i(t+1) < q_i(t+1)x_i(t+1), \end{cases} \\ 2 : q_i(t+1), \\ 3 : q_i(t+1). \end{cases} \tag{10b}$$

$$s_i(t+2) = \tilde{s}_i(t+1). \tag{11b}$$

4. A TWO-SECTOR EXAMPLE

This section illustrates the use of the Resilience IIM in a system of interdependent economic sectors. The example is adapted from Miller and Blair (2009) and connects to the example used in Barker and Santos (2010a). As-planned commodity flows for the two sectors are presented in Table 3 in thousands of € daily.

From this table, the interdependency matrix $\mathbf{A}^*$ can be derived, as explained in, for example, Lian and Haimes (2006) resulting in Equation 12.

$$\mathbf{A}^* = \begin{bmatrix} 0.15 & 0.50 \\ 0.10 & 0.05 \end{bmatrix}. \tag{12}$$

As-planned output is assumed to be equally distributed across all time periods of interest, that is $\mathbf{x}(t) = \mathbf{x}(t+1) = \ldots = \mathbf{x} = (1000, 2000)'$. It is assumed that final demand will not deviate from normal so that $\mathbf{c}^*(t) = \mathbf{c}^*(t+1) = \mathbf{c}^* = (0, 0)'$.

TABLE 3. Commodity flows in a two-sector setting (thousands of € daily).

Sectors	1	2	Final demand	Total output
1	150	500	350	1,000
2	200	100	1,700	2,000
Value added	650	1,400		
Total input	1,000	2,000		

4.1. Concave Up Decreasing Recovery vs. Concave Down Decreasing Recovery

In this section, we compare two types of recovery scenarios which are both based on a recovery period of 30 days for the directly disrupted sector. The presence of inventory is first ignored. We consider a disruption which results in a 15% inoperability in Sector 2. This corresponds to the following initial production inoperability $\mathbf{p}(0)$ in vector form in Equation 13.

$$\mathbf{p}(0) = \begin{bmatrix} 0 \\ 0.15 \end{bmatrix}. \tag{13}$$

In the case of the traditionally concave up decreasing recovery scenario the recovery coefficient matrix is assumed to be the same for every t (see Equation 14).

$$\mathbf{K} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.2 \end{bmatrix}. \tag{14}$$

Now assume that in the initially disrupted Sector 2 there is a considerable level of stock damage so that a concave down decreasing recovery scenario for this sector is more realistic. As a result, $\mathbf{K}$ becomes time dependent (see Equation 15) with small values for $\tilde{k}_{22}(t)$ in the first time periods which increase until inoperability is close to zero at $t = 30$. The values for $\tilde{k}_{22}(t)$ can be derived from the recovery path calculated with Equation 9.

$$\mathbf{K}(t) = \begin{bmatrix} 0.2 & 0 \\ 0 & \tilde{k}_{22}(t) \end{bmatrix}. \tag{15}$$

Figure 4 depicts the time-dependent inoperability levels for the two sectors in case the traditional recovery path applies to both sectors while Figure 5 shows inoperability in case of a concave down decreasing recovery scenario for Sector 2. Note that in Figure 5 the time scale on the x-axis is extended until 50 days.

FIGURE 4. Concave up decreasing recovery path for both sectors (no inventory).

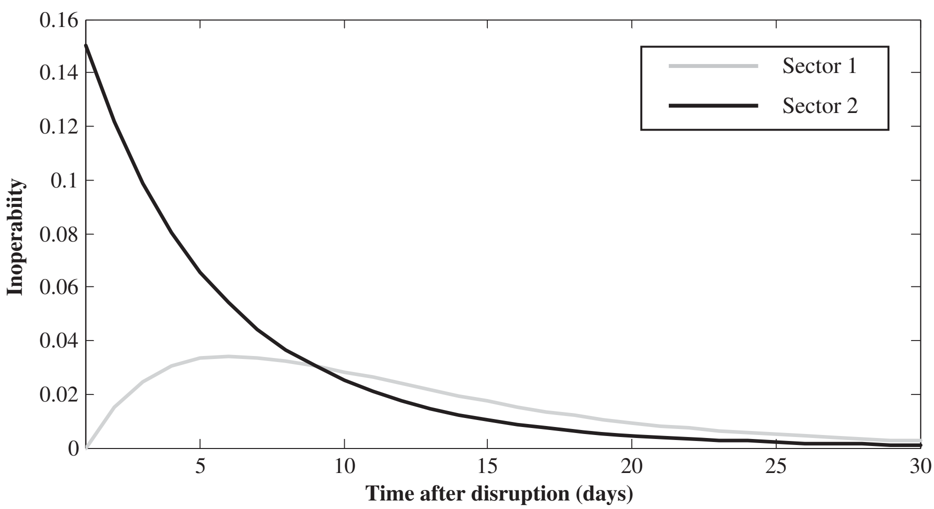
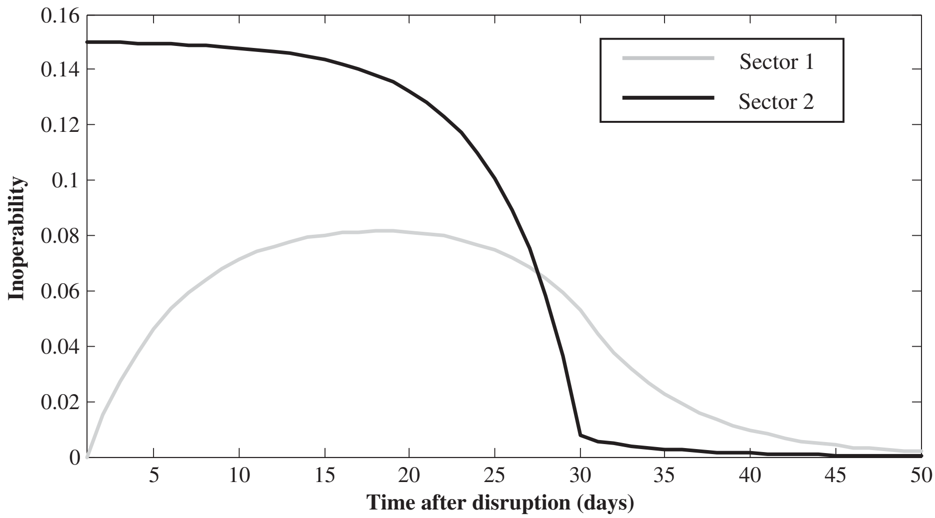


FIGURE 5. Concave down decreasing recovery path for Sector 2 (no inventory).



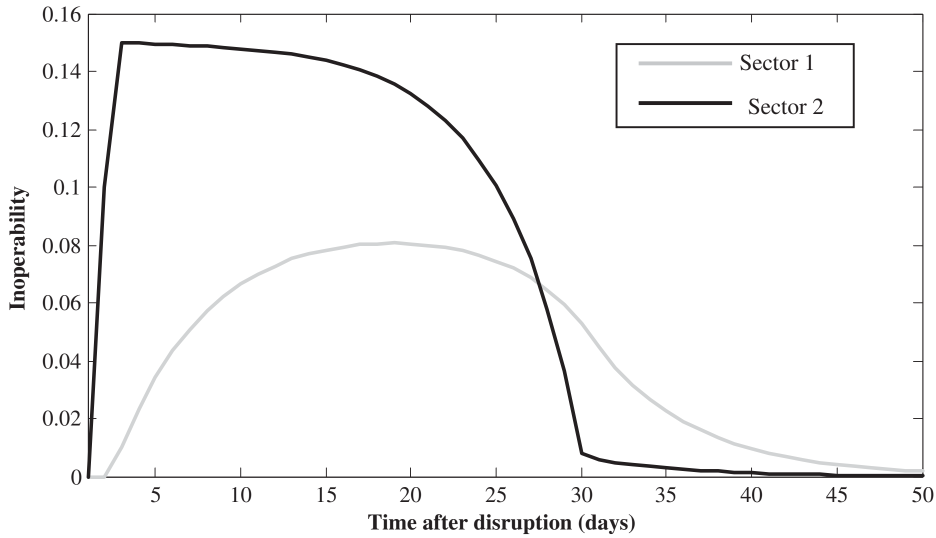
From $t = 30$ onwards, recovery in Sector 2 starts to follow a concave up decreasing path because $k_{22}(t)$ is constant and equal to 1 from $t = 30$ onwards. Because the sizes of the surfaces under the curves in Figures 4 and 5 are an indication for the size of the sectoral economic losses, it can be seen that the total economic loss, L, depends strongly on the modeller's choice of a specific recovery path. This is confirmed by the economic loss analysis. In the case of Figure 4, the economic loss is $L_{\text{concave up}} = €2,150,387$ while the loss associated with Figure 5 is $L_{\text{concave down}} = €9,795,189$ which is a difference of about a factor 4.5. Note that the higher losses in Figure 5 are also caused because Sector 1 is affected more strongly by indirect inoperability received from Sector 2 (compared with Figure 4). As a result, Sector 1 experiences higher inoperability levels and suffers longer from inoperability.

Table 4 provides values for $p_i(t)$ and $q_i(t)$ for both recovery paths for the first few time periods. It is clear that in case of the concave down decreasing scenario $p_2(t)$ and $q_2(t)$ recover very slowly compared with the concave up decreasing scenario.

TABLE 4. Production and sector inoperability in Figures 4 and 5.

	Concave up decreasing				Concave down decreasing			
t	$p_1(t)$	$p_2(t)$	$q_1(t)$	$q_2(t)$	$p_1(t)$	$p_2(t)$	$q_1(t)$	$q_2(t)$
0	0.000	0.150	0.000	0.150	0.000	0.1500	0.000	0.1500
1	0.000	0.123	0.015	0.122	0.000	0.1499	0.015	0.1499
2	0.000	0.101	0.025	0.099	0.000	0.1498	0.027	0.1498
3	0.000	0.082	0.030	0.080	0.000	0.1496	0.038	0.1497
4	0.000	0.067	0.033	0.066	0.000	0.1494	0.046	0.1495
5	0.000	0.055	0.034	0.054	0.000	0.1492	0.053	0.1493
6	0.000	0.045	0.034	0.044	0.000	0.1490	0.059	0.1490
7	0.000	0.037	0.032	0.037	0.000	0.1486	0.064	0.1488

FIGURE 6. Concave down decreasing recovery path for Sector 2 and inventory as compensation for production inoperability.



4.2. Inventory as Compensation for Sector Inoperability

This section focuses on modelling the resilience measure based on finished goods inventory. The scenario depicted in Figure 5, in which inventory is absent, is taken as a reference point. Therefore, the initial production inoperability vector and time-dependent recovery coefficient matrix, $\mathbf{K}(t)$ are the same as in the previous section. The vector for initial inventory $\mathbf{s}(0)$ is found in Equation 16.

$$\mathbf{s}(0) = \begin{bmatrix} 50 \\ 400 \end{bmatrix}. \tag{16}$$

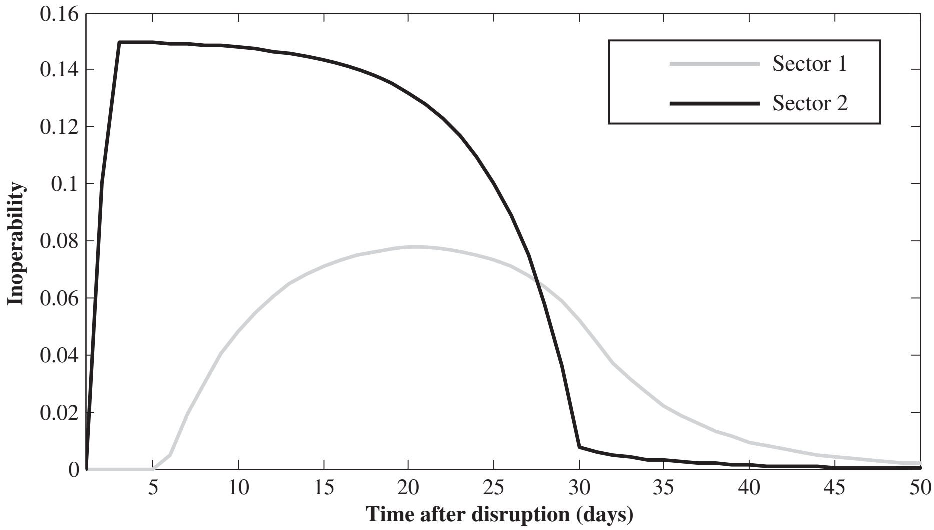
So, an initial inventory worth €450,000 in total is present in the two sectors. In the first analysis of this section, this inventory will be used to compensate for production inoperability, $p_i(t)$, only. The second analysis allows inventory to compensate for sector inoperability, $q_i(t)$.

The graphs stemming from these analyses are presented in Figures 6 and 7. In Figure 6, Sector 2 becomes inoperable at $t = 1$. Of its on-hand inventory worth 400, 300 is used during $t = 0$ to compensate for production inoperability. In $t = 1$ the remaining inventory is used to partly compensate production inoperability ($p_2(1) = 0.1499$) and consequently results in a sector inoperability of $q_2(1) = 0.099$.[7]

The economic losses associated with Figure 6 are $L_{\text{concave down}} = €9,275,036$. So, as a result of having access to an inventory worth €450,000 the economic loss is reduced

[7] It is assumed that inventory is used to completely offset production inoperability as long as it is available. Potential strategic behavior of producers to offset let us say only 50% of total inoperability, and consequently deplete their inventory less quickly, is ignored.

FIGURE 7. A concave down decreasing recovery path for Sector 2 and inventory as compensation for sector inoperability.



by €520, 153.[8] However, observing the inventory vectors $\mathbf{s}(t)$, we see that the amount of inventory in the last time period, $t = 50$ is $\mathbf{s}(50) = \begin{bmatrix} 50 \\ 0 \end{bmatrix}$. The inventory in Sector 1 is thus still intact while this sector has suffered from inoperability. The explanation for this is that Sector 1 has not experienced any *production* inoperability.

Figure 7 shows inoperability levels obtained when inventory can be used to compensate for sector inoperability. Compared with Figure 6, the onset of inoperability in Sector 1 is delayed because the inventory worth €50, 000 is used starting at $t = 2$ and keeps inoperability equal to zero until $t = 5$ when the inventory is depleted. The amount of inventory at $t = 5$ (until $t = 50$) is therefore $\mathrm{s}(5) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$. The development of production inoperability, sector inoperability and inventory over time is shown in Table 5. In case of Figure 7, the economic losses are equal to $L_{\text{concave down}} =$ €8, 974, 737. The economic loss reduction resulting from the inventory present in Sector 1 worth €50, 000 is therefore €300, 299. The total benefits from having on hand inventory at a cost of €450, 000 are equal to €820, 452. Comparing the benefits from having access to inventory in Figures 6 and 7, we conclude that the economic loss estimate may depend considerably on the ability of the model to use inventory as compensation for sector inoperability.

5. A EUROPEAN CASE STUDY

To show the value of the Resilience IIM from a policy perspective, a European case study is analysed using Input–Output data from the World Input–Output Database (WIOD, see

[8] See Figure 5: 9,795,189 – 9,275,036 = 520,153.

TABLE 5. Production and sector inoperability and inventory for Figures 6 and 7.

	s_i compensates $p_i(t)$						s_i compensates $q_i(t)$					
t	$p_1(t)$	$p_2(t)$	$q_1(t)$	$q_2(t)$	$s_1(t)$	$s_2(t)$	$p_1(t)$	$p_2(t)$	$q_1(t)$	$q_2(t)$	$s_1(t)$	$s_2(t)$
0	0.0000	0.1500	0.0000	0.0000	50	100	0.0000	0.1500	0.0000	0.0000	50	100
1	0.0000	0.1499	0.0000	0.0999	50	0	0.0000	0.1499	0.0000	0.0999	50	0
2	0.0000	0.1498	0.0099	0.1498	50	0	0.0000	0.1498	0.0000	0.1498	40	0
3	0.0000	0.1496	0.0233	0.1496	50	0	0.0000	0.1496	0.0000	0.1496	25	0
4	0.0000	0.1494	0.0343	0.1495	50	0	0.0000	0.1494	0.0000	0.1495	10	0
5	0.0000	0.1492	0.0434	0.1493	50	0	0.0000	0.1492	0.0049	0.1493	0	0
6	0.0000	0.1490	0.0509	0.1490	50	0	0.0000	0.1490	0.0190	0.1490	0	0
7	0.0000	0.1486	0.0572	0.1487	50	0	0.0000	0.1486	0.0306	0.1487	0	0

Dietzenbacher et al., 2013).[9] The case study considers a severe winter storm in Northern Europe, leaving several CIs inoperable for several weeks. The scenario was taken from Ecorys (2009). This report has selected several potential realistic future disaster scenarios for Europe, the chosen storm scenario being one of them. External experts have discussed the usefulness of the scenarios in a workshop. The EU Member States affected by the winter storm are not specified in the report. However, given the description of the scenario, the Netherlands is likely to be one of them. This country is therefore chosen for the current case study. Regarding the effect on infrastructures, the winter storm scenario encompasses the following (Ecorys, 2009):

- *Airports*: Two large airports and five smaller regional airports are severely damaged, clean-up and repairs are expected to take four to five weeks.
- *Railways*: Tens of kilometres of tracks need clearance from fallen trees and power lines.
- *Railway stations*: The Central station of City X will be affected for several months.
- *Roads*: Many bridges and roads have been damaged.
- *Electricity*: At least five main power lines (due to damaged power pylons) are severely damaged across all four affected Member States causing the entire power grid to be extremely sensitive; the restorations will take several weeks.
- *Telecommunications*: mobile networks are down in most of the region, fixed landlines are also severely damaged.

These effects are translated into infrastructure inoperability levels as presented in Table 6.

The WIOD considers 35 sectors in the National Input–Output Tables (NIOTs, see Appendix 1 for an overview of all sectors). We use the NIOT for the Netherlands for the year 2009 because this is the most recent one. The time-units are measured in days. Because the household sector is made endogenous and thus included in the inter-industry matrix, in total 36 sectors are considered in the analysis.

Eight of those sectors can be identified as CI sectors (see Table 7). Annual detailed enterprise statistics available at Eurostat (2013a) (under the topic of 'Structural Business

[9] Although the WIOD does not offer the most detailed national I–O tables, it does offer the most standardized tables for the EU. This is an advantage as the model presented must be applicable to all EU Member States. The WIOD release available at www.wiod.org on 20 February 2013 was used for this analysis.

TABLE 6. Infrastructure inoperability levels.

CI	Initial production inoperability (%)	Recovery time
Air transport	75	4 weeks/28 days
Rail transport	50	2 months/61 days
Road transport	10	2 months/61 days
Electricity	75	2 weeks/14 days
Telecommunications	75	2 weeks/14 days

TABLE 7. CI sectors in NIOT.

No.	CI
1	Air transport
2	Electricity, gas, steam and hot water supply
3	Post and telecommunications
4	Water transport
5	Land transport; transport via pipelines
6	Financial intermediation, except insurance and pension funding
7	Health and social work
8	Workforce

Statistics' (SBS)) which are available for the EU28, are used to aggregate the sector perturbations in Table 6. These enterprise statistics reveal, among other topics/labels, the production value of several hundred subsectors, those in Table 6 included. Using these SBS data, a perturbation for the electricity, gas *or* water supply sector can be transformed into a perturbation for the aggregated 'electricity, gas *and* water supply' sector as considered in the NIOTs from the WIOD. The model inputs $p_i(0)$ are then calculated as presented in the last column of Table 8. Hence, the share of a particular CI sector within its NIOT aggregate sector is multiplied by the production inoperability level mentioned in Table 6. We acknowledge that this is a rough estimate, but at the same time it provides a realistic way to introduce the initial perturbation to the model.

Data on inventory levels are derived from Statistics Netherlands (2013), which provides us with the value of the sectoral inventory levels at the end of 2008. We assume that these are the minimum inventory levels that are being maintained, considering that disasters happen unexpectedly. The inventory levels comprise both input inventories (e.g. raw materials) and output inventories (finished goods). A study from the UK indicates that stocks of raw materials and intermediate goods are actually much larger (83% of total stock value) than stocks of finished goods (Ruth and van Velzen, 2011). The inventory levels obtained from Statistics Netherlands are therefore multiplied with a factor 0.17. In addition, it is assumed that for the service sectors, inventory levels are equal to zero because services are produced and consumed at the same time ('finished services' cannot be stored). The initial inventory levels $\mathbf{s}(0)$ for the case study under consideration, are presented in Appendix 1. It can be observed that inventories are particularly high in the wholesale sector. It is assumed that sectoral annual output, $\mathbf{x}_i$, can be divided into time-invariant daily output levels, like in Anderson et al. (2007) and Barker and Santos (2010b). Donaghy et al. (2007) discuss how

TABLE 8. Estimation of initial production perturbation.

CI	Share (SBS, Eurostat 2008)	NIOT sector (WIOD)	$p_i(0)$
Electricity	0.76[a]		
Gas	0.22[a]	Electricity, gas, steam and hot water supply	$0.76 \times 0.75 = 0.57$
Water	0.02[a]		
Rail	0.09		$0.09 \times 0.50+$
Road	0.91	Land transport; transport via pipelines	$0.91 \times 0.10 = 0.14$
Pipeline	0.01		
Telecommunications	0.76	Post and telecommunications	$0.76 \times 0.75 = 0.57$
Post	0.24		
Air	–	Air	0.75

[a]Because the shares for electricity, gas and water are not available for the Netherlands, the shares of those CIs are determined by averaging the German and Belgian ones as they are neighbouring countries.

TABLE 9. Calculation of repair coefficients.

NIOT CI sector	Recovery time	Repair coefficient $\tilde{k}_{ii}$
Electricity, gas, steam and hot water supply	2 weeks/14 days	$\frac{\ln(0.57/0.01)}{14} = 0.289$
Land transport; transport via pipelines	2 months/61 days	$\frac{\ln(0.14/0.01)}{61} = 0.043$
Air transport	4 weeks/28 days	$\frac{\ln(0.75/0.01)}{28} = 0.154$
Post and telecommunications	2 weeks/14 days	$\frac{\ln(0.57/0.01)}{14} = 0.289$

this assumption can be relaxed using Marshallian computable general equilibrium models and regional econometric input–output models (REIMs).

According to Ecorys (2009), the infrastructures mentioned in Table 6 have suffered considerable stock damage. Consequently, it is assumed that in these sectors, repair activities are hampered and logistics in the immediate disaster aftermath are complex and slow. A concave down decreasing recovery path for these directly affected sectors is therefore assumed and Equation 9 is used to calculate these paths, using the information in Table 9.

Using the inputs discussed in this section and the interdependency matrix $\mathbf{A}^*$ for the Netherlands (based on WIOD I–O data for 2009) we find economic losses worth €2, 319.3 million (or €2.3 billion) for the scenario described. This is about 0.4% of Dutch GDP in 2009 (Eurostat, 2013b). Figure 8 presents the inoperability levels graphically and Table 10 shows the economic losses for this scenario. In Figure 8 there are as many curves as there are sectors in Appendix 1. The directly affected infrastructures are presented by the thick lines. The 32 indirectly affected sectors (thin lines) are named under one header in the legend. From the directly affected CIs, only the 'Electricity, gas and water' sector has access to initial inventory which can be used during the first few time periods.

FIGURE 8. Inoperability levels for the Dutch winter storm scenario.

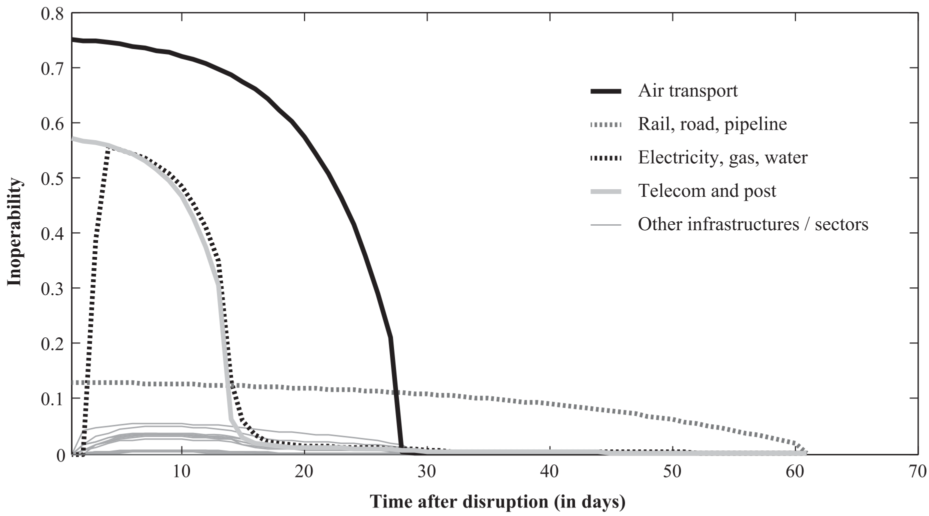


TABLE 10. Economic losses for the Dutch winter storm scenario.

No.	CI	Economic losses without inventory (million €)	Economic losses with inventory (million €)
1	Air transport	188.9	188.8
2	Electricity, gas, steam and hot water supply	614.4	481.3
3	Post and telecommunications	405.4	395.2
4	Water transport	0.7	0.5
5	Land transport; transport via pipelines	285.1	283.2
6	Financial intermediation, except insurance and pension funding	187.0	131.1
7	Health and social work	27.0	19.0
8	Household sector/workforce	544.2	379.7
	Total (8 CIs)	2,252.6	1,878.7
	Total (all 36 sectors)	3,357.5	2,319.3

During $t = 2$ inventory is depleted and this infrastructure sector becomes inoperable as well. Appendix 1 shows that all production sectors own enough inventory to compensate for indirect inoperability received from other infrastructures and sectors during the entire post-disaster period. This translates into economic losses for these sectors being equal to zero. Because the service sectors are assumed not to have any type of finished goods inventory, economic losses emerge in those sectors. The losses are relatively high in the directly affected infrastructure sectors and in the household (or workforce) sector (see Table 10). If there were no inventory (vector $\mathbf{s}(0)$ in Appendix 1 only contains zeros in this case), economic losses would have been equal to €$3,357.5$ million. This implies that in the case study under consideration, inventory reduces economic losses by 31%. Although only the electricity, gas and water sector has access to inventory, economic losses are also significantly reduced in the following CI sectors: financial intermediation, health and social work and the household sector. This finding indicates that the presence of inventory in one sector also creates benefits for dependent (infrastructure) sectors.

Considering the economic value of total inventory, or the resilience costs, at $t = 0$ (€13, 139.1 million, see Appendix 1) and the size of the residual losses (€2, 319.3 million), we are at some point on the x-axis to the right of Q opt. in Figure 1. At this point, the resilience cost curve is (quite far) above the residual loss curve. The level of overinvestment in inventories is thus sizeable in this case, even if one takes into account that finished goods inventories also have to cover other risks like an unexpected increase in demand. How, in the context of investing in inventory, key sectors can be identified is discussed in Barker and Santos (2010b). Knowing these sectors will contribute to the minimization of the sum of resilience costs and residual losses leading to an optimal level of investment in economic resilience measures.

6. CONCLUSIONS

In this paper, we have presented an inoperability input–output model (IIM) which includes economic resilience and can serve as a tool to analyse the economic impact of critical infrastructure (CI) failure. Inoperability can be interpreted as the level of dysfunction of an (infrastructure) sector. The added value of the model compared with past efforts can be found in two innovations.

The first one concerns a different approach regarding modelling recovery of CIs and economic sectors in the aftermath of a disaster. Those sectors that are directly affected by a disaster, and are suffering from considerable capital stock damage, may initially recover slowly. After some time, when repair activities and logistics are coordinated, recovery is likely to accelerate. In this case the traditionally assumed concave up decreasing recovery path can be modified and concave down decreasing recovery is deemed to be more realistic. We have shown that the size of the economic losses may differ considerably with the assumed shape of the recovery path.

The second innovation concerns the modelling of measures which delay the onset of inoperability. Finished goods inventory is an example of such measures. In previous inoperability input–output modelling efforts, inventory is used to supply to customers only if there is a physical disruption of a sector's production capacity (or 'production inoperability'). In our model however, inventory can be used to mute the supply loss resulting from a disruption in a sector or infrastructure due to any cause. In this case inventory compensates for 'sector inoperability'. The analyses indicate that the estimated size of the economic loss is smaller if inventory can be used to compensate for this type of inoperability.

The developed model in this study is called the Resilience IIM. A Dutch winter storm case study shows that the model can be used to analyse hypothetical and real past events regarding CI failures in the European Union. Input–Output data from the WIOD and sector specific statistics available at Eurostat serve as a sound basis to feed the model with data. This way, the Resilience IIM can serve as a tool to assist in approximating optimal resilience strategies where 'optimal' relates to a level of investment in resilience measures with which the total of resilience costs plus residual losses following from infrastructure failure are minimized.

Several directions for extending the model are planned. Firstly, a multiregional extension is foreseen in order to address border-crossing economic losses. This is necessary considering the multinational nature of infrastructures in the EU. Secondly, to account for uncertainty about the size of the economic losses following from disasters, a probabilistic extension is desired so that a distribution of economic losses can be generated. This will transform the Resilience IIM from an impact assessment tool into a risk assessment tool. Finally, modelling the deterioration of (infrastructure) operability is an interesting direction. In the case of a pandemic, for example (Orsi and Santos, 2010), for the workforce sector we would probably first observe an upward inoperability trend until a peak, and then downward inoperability until the end of the recovery period.

Acknowledgments

We are very grateful to Joost Santos, Bert Steenge and two anonymous referees for their valuable comments. Also we would like to thank Neil Mitchison for proofreading. The work in this article is performed within the framework of the JRC activities supporting the 'European Programme for Critical Infrastructure Protection' (EPCIP) and the 'Prevention, Preparedness and Consequence Management of Terrorism and other Security-related Risks (CIPS) programme' under contract AA 32253.

References

Akhtar, R. and J.R. Santos (2013) Risk-Based Input-Output Analysis of Hurricane Impacts on Interdependent Regional Workforce Systems. *Natural Hazards*, 65, 391–405.

Ali, J. and J.R. Santos (2012) Framework for Evaluating Economic Impact of IT Based Disasters on the Interdependent Sectors of the US Economy. *Proceedings of the 2012 IEEE Systems and Information Engineering Design Symposium*, University of Virginia, Charlottesville, 27 April 2012, 1–6.

Anderson, C.W., J.R. Santos and Y.Y. Haimes (2007) A Risk-Based Input-Output Methodology for Measuring the Effects of the August 2003 Northeast Blackout. *Economic Systems Research*, 19, 183–204.

Barker, K. and J.R. Santos (2010a) Measuring the Efficacy of Inventory with a Dynamic Input-Output Model. *International Journal of Production Economics*, 126, 130–143.

Barker, K. and J.R. Santos (2010b) A Risk-Based Approach for Identifying Key Economic and Infrastructure Systems. *Risk Analysis*, 30, 962–974.

Dietzenbacher, E., B. Los, R. Stehrer, M.P. Timmer and G.J. de Vries (2013) The Construction of World Input-Output Tables in the WIOD Project. *Economic Systems Research*, 25, 71–98.

Donaghy, K.P., N. Balta-Ozkan and G.J.D. Hewings (2007) Modeling Unexpected Events in Temporally Disaggregated Econometric Input-Output Models of Regional Economies. *Economic Systems Research*, 19, 125–145.

Ecorys (2009) Strengthening the EU Capacity to Respond to Disasters: Identification of the Gaps in the Capacity of the Community Civil Protection Mechanism to Provide Assistance in Major Disasters and Options to Fill the Gaps – A Scenario-Based Approach. AE18176, Final Report, Ecorys research and consulting, Rotterdam.

European Council (2008) *EC Council Directive 2008/EC/114*. Available at http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:345:0075:0082:EN:PDF (accessed 22 February 2013).

Eurostat (2013a) Available at http://epp.eurostat.ec.europa.eu/portal/page/portal/european_business/data/database (accessed 10 February 2013).

Eurostat (2013b) Available at http://epp.eurostat.ec.europa.eu/portal/page/portal/national_accounts/data/main_tables (accessed 26 February 2013).

Greenberg, M., C. Haas, A. Cox Jr., K. Lowrie, K. McComas and W. North (2012) Ten Most Important Accomplishments in Risk Analysis, 1980–2010. *Risk Analysis*, 32, 771–781.

Haimes, Y.Y., B.M. Horowitz, J.H. Lambert, J.R. Santos, C. Lian and K.G. Crowther (2005a) Inoperability Input-Output Model for Interdependent Infrastructure Sectors. I: Theory and Methodology. *Journal of Infrastructure Systems*, 11, 67–79.

Haimes, Y.Y., B.M. Horowitz, J.H. Lambert, J.R. Santos, K.G. Crowther and C. Lian (2005b) Inoperability Input-Output Model for Interdependent Infrastructure Sectors, II: Case Studies. *Journal of Infrastructure Systems*, 11, 80–92.

Koetse, M.J. and P. Rietveld (2012) Adaptation to Climate Change in the Transport Sector. *Transport Reviews: A Transnational Transdisciplinary Journal*, 32, 267–286.

Kujawski, E. (2006) Multi-Period Model for Disruptive Events in Interdependent Systems. *Systems Engineering*, 9, 281–295.

Leontief, W.W. (1951a) Input-Output Economics. *Scientific American*, 185, 15–21.

Leontief, W.W. (1951b) *The Structure of the American Economy, 1919–1939*. 2nd ed. New York, Oxford University Press.

Lian, C. and Y.Y. Haimes (2006) Managing the Risk of Terrorism to Interdependent Infrastructure Systems Through the Dynamic Inoperability Input-Output Model. *Systems Engineering*, 9, 241–258.

Miller, R.E. and P.D. Blair (2009) *Input-Output Analysis: Foundations and Extensions*. 2nd ed. Cambridge, Cambridge University Press.

Orsi, M.J. and J.R. Santos (2010) Incorporating Time-Varying Perturbations into the Dynamic Inoperability Input-Output Model. *IEEE Transactions on Systems, Man, and Cybernetics, Part A: Systems and Humans*, 40, 100–106.

Rose, A.Z. (2007) Economic Resilience to Natural and Man-Made Disasters: Multidisciplinary Origins and Contextual Dimensions. *Environmental Hazards*, 7, 383–398.

Rose, A.Z. (2009) A Framework for Analyzing the Total Economic Impacts of Terrorist Attacks and Natural Disasters. *Journal of Homeland Security and Emergency Management*, 6, 1–27.

Rose, A.Z. and S. Liao (2005) Modeling Resilience to Disasters: Computable General Equilibrium Analysis of a Water Service Disruption. *Journal of Regional Science* 45, 75–112.

Ruth, F. and M. van Velzen (2011) The Inventory to Sales Ratio in Manufacturing; A Real Leading Business Cycle Indicator. *Discussion Paper(201112)*, Statistics Netherlands, The Hague/Heerlen.

Santos, J.R. and Y.Y. Haimes (2004) Modeling the Demand Reduction Input-Output (I-O) Inoperability Due to Terrorism of Interconnected Infrastructures. *Risk Analysis*, 24, 1437–1451.

Statistics Netherlands (2013) Available at http://statline.cbs.nl/ (accessed 4 March 2013)

APPENDIX 1. Sectors in the WIOD National Input–Output Table (NIOT) for the Netherlands, annual and daily as-planned production levels (year 2009), initial production inoperability levels, initial inventory levels and economic losses.

Sectors NIOT	x_i year (million €)	x_i day (million €)	$p_i(0)$	$s_i(0)$ (million €)	L_i (million €)
Agri., Hunting, Forestry and Fishing	21,458	58.8	0	213.1	0.0
Mining and Quarrying	18,922	51.8	0	50.5	0.0
Food, Beverages and Tobacco	44,006	120.6	0	913.2	0.0
Textiles and Textile Products	2,186	6.0	0	75.7	0.0
Leather, Leather and Footwear	257	0.7	0	9.8	0.0
Wood and Products of Wood and Cork	2,160	5.9	0	63.7	0.0
Pulp, Paper, Printing and Publishing	14,713	40.3	0	121.3	0.0
Coke, Refined Petr. and Nuclear Fuel	10,276	28.2	0	126.3	0.0
Chemicals and Chemical Products	27,548	75.5	0	934.2	0.0
Rubber and Plastics	4,456	12.2	0	158.9	0.0
Other Non-Metallic Mineral	5,153	14.1	0	51.2	0.0
Basic Metals and Fabricated Metal	15,796	43.3	0	651.4	0.0
Machinery, Nec	13,587	37.2	0	579.5	0.0
Electrical and Optical Equipment	11,950	32.7	0	366.1	0.0
Transport Equipment	7,352	20.1	0	305.9	0.0
Manufacturing, Nec; Recycling	7,904	21.7	0	183.6	0.0
Electricity, Gas and Water Supply	30,308	83.0	0.57	108.9	481.3
Construction	73,397	201.1	0	1,229.3	0.0
Sale, Maintenance and Rep. of Motor Veh. and Motorcycl.; Ret. Sale of Fuel	13,614	37.3	0	1,395.0	0.0
Wholesale Trade and Com. Trade, Except of Motor Veh. and Motorcycles	60,251	165.1	0	4,292.8	0.0
Ret. Trade, Except of Motor Veh. and Motorcycles; Rep. of Household Goods	28,177	77.2	0	1,308.7	0.0
Hotels and Restaurants	16,385	44.9	0	0.0	43.6
Inland Transport	17,818	48.8	0.13	0.0	283.2
Water Transport	3,144	8.6	0	0.0	0.5
Air Transport	4,106	11.2	0.75	0.0	188.8
Other Supporting and Auxiliary Transport Act; Act of Travel Agencies	14,381	39.4	0	0.0	47.5
Post and Telecommunications	21,234	58.2	0.57	0.0	395.2
Financial Intermediation	70,915	194.3	0	0.0	131.1
Real Estate Activities	60,838	166.7	0	0.0	97.4
Renting of M and Eq. and Other Bus Act	115,628	316.8	0	0.0	178.2
Public Admin and Defence; Compulsory Social Security	66,443	182.0	0	0.0	15.9
Education	32,992	90.4	0	0.0	9.5
Health and Social Work	66,688	182.7	0	0.0	19.0
Other Community, Social and Personal Services	34,045	93.3	0	0.0	44.3
Private Households with Emp. Persons	2,325	6.4	0	0.0	4.2
Workforce	210,501	576.7	0	0.0	379.7
Total				13,139.1	2,319.3