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MODELING INTERDEPENDENCIES OF CRITICAL INFRASTRUCTURES AFTER HURRICANE SANDY

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Abstract

This paper evaluates the level of inoperability and the resilience of the critical infrastructure networks of the New York Metropolitan Area affected by Hurricane Sandy in October 2012. The region analyzed in the case study includes New York City and some New Jersey counties. The highly concentrated critical infrastructures of this area are vulnerable to the direct impact of catastrophic events, such as hurricanes, as well as to the disruptive cascading effects that are spread through the existing interdependencies. The inoperability Input-Output model, developed by Haimes and Jiang, is selected to numerically define the degree of interconnection among these systems and quantify the effect of an external perturbation on the network's functionality. Based on the model's results, a new indicator called the "inoperability ratio" is introduced to identify some initiatives that policymakers can implement during the restoration process. These actions reduce the inoperability ratio to prevent cascading effects and to speed up the recovery process.

1. INTRODUCTION

The beginning of the new century is characterized by an increased number of natural and man-made catastrophic events taking place around the world, therefore the study of critical infrastructures (CIs) has faced new challenges to improve their security. In that sense, a series of actions at the European Union Level, such as the EPCIP (European Programme for Critical Infrastructure Protection) [1] are taking place. Similar actions are also taking place in other countries such as in US (e.g. National Infrastructure Security Plan in the United States). Lately, attention is focused on reducing the effects and protecting people and businesses against these extreme events by improving their resilience at the community level [2]. This is described as an increase in their ability to withstand the impact and the consequences of similar, as well as more powerful, disruptive events and to recover from them in the shortest amount of time possible [3; 4]. In particular, this

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goal can be achieved by limiting the damage reported during these events by what are known as "critical infrastructure (CI) sectors," which represent the “backbone” of the functioning of the United States economy and society. Their interconnectivity cannot be neglected when planning to increase their resilience [5; 6]. This backbone represents strong points of the infrastructures, which allows for their proper functioning in normal conditions, as well as one of their weakest points, since it allows a perturbation to a sector to easily spread to other interconnected sectors. These cascading effects have started to be considered in the world community to analyze disasters. In particular, Pescaroli and Alexander (2016) [7] proposed a new theoretical approach to cascading disasters that can be seen as an alignment of vulnerabilities that are latent in the global society. Therefore, although cascading failures cannot be prevented, latent vulnerabilities can be understood and addressed before the trigger events occur. Their suggestion is to shift from *risk scenario based* on hazard to *vulnerability scenarios based*. In other words, while it is not possible to know which events can happen at the macroscopic level, we can identify the sensitive nodes that are capable to generate secondary events at the smallest scale.

The interconnections among the CIs sectors can be analyzed with mathematic models that allow numerical values to be given to these interdependencies, based on economic data, and the way this network is affected by the disruptive event to be understood. Different frameworks can be used to assess disaster consequences at the micro-, meso-, and macroeconomic scale. Their application can include both an *ex post* loss quantification and an *ex ante* risk evaluation, which in turn restrains the effectiveness of specific models. Among several applicable models, this analysis adopts the Inoperability Input-Output Model (IIM) developed by as an adaptation of the Leontief input-output (I-O) model for the economy [8; 9]. The original I-O model is used by several researchers and analysts studying economic interdependency among industry sectors. Rose et al. [10]; Rose [11]; Cho et al. [12] apply the I-O model to address electricity lifeline disruptions caused by earthquakes by estimating the regional economic impacts of this disruption. Olsen et al. [13] used it to address the risk of flooding and evaluate the best strategy for the implementation of flood protections, while Alcantara and Padilla [14] develop a method based on the I-O model to determine the key sectors in the final consumption of energy through the analysis of energy demand elasticities. Similarly, several authors use the IIM to conduct studies on the effects of a perturbation event on the network of CI systems. Starting from the original formulation and its extension developed in [8] [15] [16] [17] [18] implement the IIM to analyze the impact and the spread of terrorism-induced perturbations due to interconnectedness among economic systems. Lian and Haimes [19] use the model in its dynamic extension (DIIM) to study the risk of a terroristic attack and the recovery of interdependent infrastructure systems from it. Crowther and Haimes [20] present three illustrative case studies that adopt the IIM calculations to calculate the cascading consequences from several threats to power infrastructure vulnerabilities for risk assessment, to evaluate the effect of the implementation of risk management policies, and to obtain optimal risk management policies by combining the IIM with cost-of-recovery model developed for a specific sector. Finally, Wei et al. [21] propose the IIM for supply chains to assess the impacts of disruptive events on supply chain networks, evaluating the coefficients of the interdependency matrix A by defining a new parameter called the Ordered Weighted Averaging (OWA) Operator to describe the cascading effects of disruptions to interdependent supply chain components.

Galbusera et al. [22] introduced a modified version of the Inventory-DIIM (I-DIIM) initially proposed by Barker and Santos [23] where a dynamic inoperability input-output model (DIIM) is combined with a database of inventory policies, inventory costs and economic loss reduction. In detail, they studied how the inventory levels of a network of producers and service providers within a region can drastically affect resilience to critical events and the related disruption costs.

Martinelli et al. [24] analyzes the impact of natural disasters such as earthquakes in the Bay area using a modified IIM that takes into account the economic interdependencies between industries and lifelines using autonomy curves. Kammouh et al. [25] used a large database of damage caused by earthquakes to derive restoration fragility curves for different infrastructure types where the interdependency among them is analyzed.

Recently, Galbusera and Giannopoulos [26] reviewed how different disaster modeling aspects have been incorporated in recent contributions exploiting I/O techniques, taking into account both demand and supply-sided perturbation triggers. I/O models offer linearity as well as a straight way of outlining inter-industry linkages and demand structure, but they are more rigid than Computable General Equilibrium (CGE) frameworks that are able to represent a large spectrum of demand- and supply-side elasticities, therefore they are more flexible, but more computationally expensive. In disaster analysis, CGE models are often considere as underestimators of economic losses, while I/O models are often considered as overestimators [27].

The IIM is firstly adopted in this paper to model the CI network interconnectivity, to identify and rank different types of dependencies. Secondly, it allows the spread of cascading effects through the systems network of the New York metropolitan area hit by Hurricane Sandy in October 2012 to be better understood. The results of the model in terms of inoperability are used to help policymakers identify the best intervention strategy to implement in response to future similar events. For this purpose, a new parameter, named the inoperability ratio, is evaluated to numerically describe the influence that the damage affecting one sector had on the others. Based on some assumptions, this parameter is calculated for a perturbation, also defined as a functionality reduction, that the disruptive event induces on the "utilities," "liquid fuel," and "transportation" sectors. Different values of this parameter find a realistic correspondence in the events that took place during Hurricane Sandy, justified by several examples regarding the influence among these sectors in terms of indirect damage. This ratio is then used to identify the priority initiatives among the many that can be implemented to reduce the impact of future disruptive events like Sandy on the network of CIs. The priority initiatives on which to focus are those that reduce this parameter to a value as close to zero as possible, to limit the inoperability induced in a sector because of damage occurring to another one. Furthermore, according to the numeric value of this ratio, it is possible to organize these selected actions by distinguishing between primary and secondary initiatives.

The dynamic extension of the model is also developed to evaluate the recovery of the "utilities" sector in the aftermath of Hurricane Sandy. To run the model, both real and estimated data have been considered. The real data refers to the percentage of customers affected by power outages in the area due to Sandy, which defines the inoperability of the sector at the occurrence of the event. On the other hand, the recovery time and the inoperability achieved after it are assumed on the basis of information collected by the New York City Government [28] and Lian and Haimes [19], among the many authors.

This paper is organized as follows: the following section introduces the formulation and the supporting database for the application of the methodology in its static and dynamic definitions; then, the analysis focuses on the application of the methodology to the case study of Hurricane Sandy's impact on the New York metropolitan area, providing some information about its unique characteristics and illustrating the calculation of the inoperability ratios and the selection of priority initiatives; finally, the conclusions obtained at the end of the research are listed.

2. PROPOSED METHODOLOGY TO ASSESS THE INTERDEPENDENCY OF CRITICAL INFRASTRUCTURES

The Inoperability Input-Output Model (IIM) is proposed by Haimes and Jiang [29] as an adaptation of the original input-output (I-O) model developed by Leontief and Leontief [9] to define the degree of interdependency among industry sectors of a national or regional economy. Based on the same economic data of the Leontief model, the IIM assesses the impact of disruptive events on the network of interconnected economic systems in terms of inoperability. The authors define inoperability as the “inability of a system to perform its intended function”, which is a function of the impact of the external perturbation event, as well as of the network interconnectedness.

The model quantifies these interactions among interdependent systems based on the economic data provided by the Bureau of Economic Analysis (BEA, 2016). This supporting database defines the national input-output accounts among industries in terms of their production and consumption of goods through what are known as “make” and “use” matrices. The “make” matrix represents the interaction between industries and commodities in terms of production of commodities. It is an “industry-by-commodity” matrix in which each element represents the monetary value of each commodity, found along the columns, produced by each industry, found along the rows, expressed in millions of dollars. It is given by Equation (1):

$$V = \begin{bmatrix} v_{11} & \cdots & v_{1j} & \cdots & v_{1m} \\ \vdots & & \vdots & & \vdots \\ v_{i1} & \cdots & v_{ij} & \cdots & v_{im} \\ \vdots & & \vdots & & \vdots \\ v_{n1} & \cdots & v_{nj} & \cdots & v_{nm} \end{bmatrix} \tag{1}$$

where V is the “make” matrix and v_{ij} is the monetary value in millions of dollars of each commodity j produced by each industry i.

On the other hand, the “use” matrix defines the same interaction in terms of consumption of commodities. It is a “commodity-by-industry” matrix in which each element represents the monetary value of each commodity, found along the rows, consumed by each industry, found along the columns, expressed in millions of dollars. It is given by Equation (2):

$$U = \begin{bmatrix} u_{11} & \cdots & u_{1j} & \cdots & u_{1n} \\ \vdots & & \vdots & & \vdots \\ u_{i1} & \cdots & u_{ij} & \cdots & u_{in} \\ \vdots & & \vdots & & \vdots \\ u_{m1} & \cdots & u_{mj} & \cdots & u_{mn} \end{bmatrix} \tag{2}$$

where U is the “use” matrix and u_{ij} is the monetary value in millions of dollars of each commodity i consumed by each industry j.

A combination of these matrices is used to calculate what is known as the Leontief technical coefficient matrix A, which numerically defines the degree of interdependency among economic industries. Firstly, each element of the “make” and “use” matrices is divided by its respective column summation. For the former, it represents the total commodity input y_j and overall defines the total commodity input vector (y^T) defined in Equation (3). For the latter, it is the total industry inpu*t* x_i and together with the others defines the total industry input vector (x^T) (Equation (4)).

$$y^T = \begin{bmatrix} y_1 = \sum_i v_{i1} & \cdots & y_j = \sum_i v_{ij} & \cdots & y_m = \sum_i v_{im} \end{bmatrix} \tag{3}$$

$$x^T = \begin{bmatrix} x_1 = \sum_i u_{i1} & \cdots & x_j = \sum_i u_{ij} & \cdots & x_m = \sum_i u_{im} \end{bmatrix} \tag{4}$$

The matrices so obtained are what are known as the normalized “make” and “use” matrices, defined in Equations (5) and (6):

$$\hat{V} = V\left[diag(y)\right]^{-1} \Leftrightarrow \left\{ \hat{v}_{ij} = \frac{v_{ij}}{y_j} \right\} \tag{5}$$

$$\hat{U} = U\left[diag(y)\right]^{-1} \Leftrightarrow \left\{ \hat{u}_{ij} = \frac{u_{ij}}{x_j} \right\} \tag{6}$$

where $\hat{V}$ is the normalized “make” matrix, ˆij is the normalized monetary value of each commodity *j* produced by each industry *i*, y_j is the total commodity input, *diag(y)* is a diagonal matrix of yj terms, $\hat{U}$ is the normalized “use” matrix, $\hat{u}_{ij}$ is the normalized monetary value of each commodity *i* consumed by each industry *j*, x_j is the total industry input, and *diag(x)* is a diagonal matrix of x_j terms.

These matrices are then multiplied to define the “industry-by-industry” interdependency matrix *A*

$$A = \hat{V}\hat{U} \Leftrightarrow \left\{ a_{ij} = \sum_k \hat{v}_{ik}\hat{u}_{kj} \right\} \tag{7}$$

where *A* is the technical coefficient interdependency matrix and a_{ij} is the degree of dependency of the production output of each industry *i* from the production input of each industry *j*.

The interdependency matrix *A* defines the interaction among industries at the national U.S. economic level in terms of production of goods. The production output of one industry is used as input for the calculation of the total production output of another industry. In order to provide a more accurate analysis of these interdependencies for a specific region of interest, this matrix can be specialized through what are known as RIMS II accounts. Provided by the BEA's Regional Economic Analysis Division, these are database of regional multipliers calculated on the basis of regional personal income and wage-and-salary data. As reported by Haimes et al. [16], “empirical tests suggest that regional multipliers can be used as surrogates for time-consuming and expensive surveys without compromising accuracy”. Also, as reported by [30], the focus of the input-output analysis on the network of interconnected sectors of a specific region can give valid results since interregional feedbacks are small and do not influence this analysis applied to a closed region.

The regional multipliers are obtained from the location quotients for regional decomposition calculated through Equation (8):

$$l_i = \frac{\hat{x}_i^R / \hat{x}_s^R}{\hat{x}_i / \hat{x}_s} \tag{8}$$

where l_i is the location quotient for the i^{th} industry, $\hat{x}_i^R$ is the regional output for the i^{th} industry, $\hat{x}_s^R$ is the total regional output for all regional-level industries, $\hat{x}_i$ is the national output for the i^{th} industry, and $\hat{x}_s$ is the total national output for all national-level industries.

Location quotients are used to regionalize the national technical coefficient matrix A and to obtain the regional interdependency matrix A^R as in Equation (9):

$$A^R = diag\left[\min(l, \Sigma)\right] A \Leftrightarrow \left\{a_{ij}^R = \min(l_i, 1) a_{ij}\right\} \tag{9}$$

$$diag\left[\min(l, \Sigma)\right] = diag\begin{bmatrix} \min(l_1, 1)a_{11} & 0 & \cdots & 0 \\ 0 & \min(l_2, 1)a_{22} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & \min(l_n, 1)a_{nn} \end{bmatrix} \tag{10}$$

In Equation (9), A^R is the regional technical coefficient interdependency matrix, l is the location quotients vector, Σ is the unity vector, a_{ij}^R is the degree of dependency of the production output of each regional industry i from the production input of each regional industry j, a_{ij} is the degree of dependency of the production output of each industry i on the production input of each industry j, and l_i is the location quotient for the i^{th} industry.

Among the several models developed by Haimes and Jiang [29], what is known as the demand-reduction (or demand-side) IIM is used to analyze the impact of Hurricane Sandy in the area under analysis. The model is derived from the combination of the original IIM with the data provided by BEA regarding the national input-output economic accounts. Inoperability is quantified as a reduction of production caused by perturbations to the demand, rather than as the degraded capacity to deliver the intended output, as evaluated by the original model. The demand-reduction IIM evaluates how the inoperability of a perturbed system influences the other interdependent systems with various degrees of impact through Equation (11):

$$q = A^* q + c^* \tag{11}$$

$$c_i^* = \frac{\hat{c}_i - \tilde{c}_i}{\hat{x}_i} \tag{12}$$

$$a_{ij}^* = a_{ij}\left(\frac{\hat{x}_j}{\hat{x}_i}\right) \tag{13}$$

$$q_i = \frac{\hat{x}_i - \tilde{x}_i}{\hat{x}_i} \tag{14}$$

where c^* is the demand-side perturbation vector in which each element is defined as the ratio between the decrease in the final demand and the "as-planned" production (Equation (12)), A^* is the demand-side interdependency matrix, whose elements are defined on the basis of the Leontief technical coefficients and the ratio between the "as-planned" productions of the interconnected industries (Equation (13)), and q is the demand-side inoperability vector, whose elements represent the inoperability of single industries defined as the normalization of the reduction of their production with respect to the 'as-planned' production (Equation (14)).

For the purpose of the present analysis, Equation (15) is obtained for the demand-reduction regional IIM. Each element of Equation (15) assumes the same meaning described in Equations (12), (13), and (14) but refers to a regional scale.

$$q^R = A^{*R} q^R + c^{*R} \tag{15}$$

The corresponding demand-reduction regional matrix A^{*R} can be written as in Equation (16):

$$A^{*R} = \left[\left(diag\left(\hat{x}^R \right) \right)^{-1} A^R \left(diag\left(\hat{x}^R \right) \right) \right] \Leftrightarrow \left\{ a_{ij}^{*R} = a_{ij}^R \left(\frac{\hat{x}_j^R}{\hat{x}_i^R} \right) \right\} \tag{16}$$

As described, this model is defined as the static IIM since it allows the relationships and consequent interactions among industries for a specific year and area of interest to be described, creating a fixed "picture" of the situation of a national and regional economy.

The values of inoperability provided by the method for the sectors interconnected with the perturbed sector are extremely low when compared to the inoperability of the sector subjected to functionality reduction, which has a value practically equal to the percentage of perturbation. These values can be used to define sector rankings but, due to their dimensions, do not define realistic percentages of inoperability. A solution proposed to obtain more valuable information is to use these values as magnitudes so as to scale the inoperability of the other sectors proportionally to that of the perturbed sector. The new percentages of inoperability can be obtained as follows:

$$q_{jscaled}^R = \frac{q_j^R}{\sum q_j^R} q_p^R \tag{17}$$

where $q^R_{jscaled}$ is the new value of induced inoperability, calculated with the regional model and referring to the j^{th} sectors not directly subjected to functionality reduction, q^R_j is the original value of inoperability, and q^R_p is the inoperability of the sector affected by functionality reduction.

There is a constant linear relationship between the induced inoperability on one sector and the inoperability of the sector subjected to functionality reduction: an increase of the latter corresponds to a proportional increase of induced inoperability in the other sectors. This proportionality can therefore be taken into account through a new parameter, called inoperability ratio, which defines the inoperability induced in a sector as a function of the inoperability of the perturbed sector. Equation (18) shows that it is calculated as the ratio between the inoperability induced in the network's sectors and the inoperability of the sector affected by functionality reduction, also called direct inoperability.

$$\xi_{pj} = \frac{q^R_{jscaled}}{q^R_p} \tag{18}$$

where ξ_{pj} is the inoperability ratio, $q^R_{jscaled}$ is the new value of induced inoperability, calculated with the regional model and referring to the j^{th} sectors not directly subjected to functionality reduction, and q^R_p is the inoperability of the sector affected by functionality reduction.

This ratio does not change with the increase of functionality reduction or perturbation, therefore it can be considered as a valuable value for the evaluation of both the inoperability induced and the degree of interconnections.

2.1 Dynamic behavior of infrastructure inoperability

Lian and Haimes [19] and Haimes et al. [16] also developed what is known as the dynamic IIM, a development that “supplements and complements the static IIM”. This dynamic extension of the original IIM allows for a better assessment and comprehension of the way industries recover from their inoperability during the recovery phase, according to their ability to “bounce back” to the condition they had before the event. Therefore, the dynamic IIM is suitable to describe the recovery of CI sectors after their operability is interrupted by either natural disasters or terrorist attacks. Different types of recovery functions can be selected depending on the system and society preparedness response (e.g. linear, exponential, trigonometric) [4]. Since no information regarding the preparedness and societal response are available, but it is known that the region affected by the Hurricane is rich in term of available resources, it is reasonable to assume an exponential recovery function that can be used when the societal response is driven by an initial inflow of resources, but then the rapidity of recovery decreases as the process nears its end [4]. Therefore, the model that describes the recovery phase is characterized by an exponential function reported in Equation (19):

$$q_i(t) = e^{-k_i(1-a_{ii}^*)t} q_i(0) \tag{19}$$

where $q_i(0)$ is the inoperability of *i* sector at initial perturbation ($t=0$) ranging between 0 and 1, $q_i(t)$ is the inoperability of *i* sector during the recovery phase for time $0<t<T_i$, a_{ii}^* is the diagonal element of the demand-reduction matrix A^* or A^{R*} and k_i is the *interdependency recovery rate* calculated with Equation (20):

$$k_i = \frac{\lambda}{\tau}\left(\frac{1}{1-a_{ii}^*}\right) = \frac{\ln\left[q_i(0)/q_i(T_i)\right]}{T_i}\left(\frac{1}{1-a_{ii}^*}\right) \tag{20}$$

in which λ is the recovery constant, representing the ratio between the sector *i* inoperability, evaluated when initial perturbation occurs and when the recovery time is reached, τ is the recovery time T_i, $\frac{\lambda}{\tau}$ is the recovery rate parameter, and $q_i(T_i)$ is the inoperability of *i* sector at recovery time T_i. In particular, the interdependency recovery rate k_i, expressed in Equation (20) through a ratio, defines how fast the inoperability is recovered.

The inoperability $q_i(T_i)$, as well T_i, can be presumed based on the application of risk management actions or obtained from the analysis of damage data regarding the disruptive event and the consequent recovery time estimation. Very small values of a_{ii}^* do not influence the recovery rate significantly, but they contribute to reduce the recovery rate. On the other hand, greater a_{ii}^* defines a greater recovery rate, meaning that the interdependency of the disrupted sector on the others reduces recovery time.

2.2 Definition of risk

According to Pescaroli and Alexander (2018) [31] there are different types of risks at the community level that are listed below:

1. **Compound risk** refers to the environmental domain, or to the concurrence of natural events. Eventually it can be correlated with different patterns of extreme impacts caused by climate change.
2. **Interacting risk** refers to the domain of physical relations developed in the natural environment and to its casual chains. They focus on the area in which hazard interacts with vulnerability to create disaster risk (it is analyzed in geophysics and physical geography).

3. **Interconnected risk** include the complex interactions between human, environment, and technological systems. Interconnected risk may be referred to as the physical interdependencies that allows societal interactions, and thus a pre-condition for cascading risk.

4. **Cascading risk** is associated with the anthropogenic domain and the vulnerability component of risk. This results in a disaster escalation process.

Compound, interacting, interconnected, and cascading risk tend to be different component of hazards and vulnerabilities. While compound risk can be mostly associated with the physical dimension of hazards, interacting and interconnected risk gradually increase the focus on the vulnerability component. Thus they become the centre of cascading risk. Hurricane Sandy that will be described in detail in the next section encompasses all the possible joint effects of compounding, interacting, interconnected and cascading risks [32; 31].

3. CASE STUDY: HURRICANE SANDY'S IMPACT ON THE NEW YORK METROPOLITAN AREA

3.1 Overview

Hurricane Sandy was one of the most remarkable natural catastrophic events that took place over the past few years. It was the last hurricane of the 2012 Atlantic season that affected the Atlantic coast of North America, causing human casualties and billions of dollars in damage to houses, businesses, infrastructures, and other facilities located in countries such as Cuba, the Bahamas, and the United States. People, mass media, and government organizations still refer to it as a “Superstorm” due to its unique features and strength. One of its most distinctive characteristics was its unusual westbound track caused by its interaction with two other weather systems that were taking place in the Atlantic Ocean around that time. This occurrence not only blocked the common eastern turn that characterizes the area's hurricanes, but also intensified the storm winds and increased its extent up to 1800 km in diameter. Figure 1 gives an idea of the size and the speed of Sandy's winds while it was moving along the U.S. Atlantic coast.

Figure 1

The storm winds not only caused direct damage, but also contributed to the generation of a storm surge that caused flood damages (*interacting risk*), while concurrent cold air flowing from the Arctic intensified cold weather and caused snow storms inland (*compounding risk*). Its impact was also amplified by the superposition of multiple events that took place simultaneously when the storm hit the U.S. mainland in New Jersey. In fact, it made landfall exactly at high astronomical tide during a full moon, enhancing the effect of the storm surge waters that the high-speed winds were pushing towards the coast. Consequently, the storm surge that characterized its impact set record-breaking levels of surge waters and wave heights in New York, New Jersey, and Connecticut. For example, a storm surge of 9.56 *ft* above normal tide levels was reported at Battery Park, on the southern tip of Manhattan [33]. Overall, more than 1000 km of U.S. coastline were impacted mostly by the storm surge generated by Hurricane Sandy. The hurricane has shown an unusual track that differs from the usual one along the east coast. Indeed, the landfall perpendicular to the coast has amplified the effects of the storm on infrastructure.

One of the most affected regions along Sandy's path was the metropolitan area of New York, evidenced in Figure 2.

Figure 2

Sandy impacted a geographical area of strategic importance to the US economy. It has a dense population and a high concentration of industrial plants and financial networks, such as the New York Stock Exchange (*interconnected risk*).

Several reasons lead this analysis to focus on the events that occurred in New York City and certain counties in New Jersey that fall into this metropolitan area. On one hand, this area is not commonly associated with hurricane activity, due to their tendency of moving away from the U.S. mainland after impacting the southern states. Hurricane Sandy was only the third hurricane that hit New Jersey in its history [34], corresponding to a 1% annual probability of occurrence of similar catastrophic events during the season, as assessed by Colorado State University (http://tropical.colostate.edu). On the other hand, communities are unprepared and vulnerable against such kinds of extreme events, causing this area to suffer the most damage and economic losses due to the hurricane itself and its effects, such as flooding, the storm surge, and high-speed winds. Another reason is that the hurricane impacted an area that is characterized by a very developed network of CI sectors, whose complexity and extent represent its most distinctive feature, as well as the cause of its vulnerability to a broad range of disruptive events.

The composite nature of the hazard and the loss of highly-ranked CI triggered a wide range of secondary crises that escalated in a non-linear manner. While the emergency responders had to tackle leaks from refineries and chemical plants, or fires in houses, the President of the USA made a new declaration of emergency regarding the prolonged power outages and the damage to the production and distribution chain of gasoline and distillates (cascading risk). An official report (Blake et. al., 2013) attributed around 50 deaths to the joint effect of extended power outages and cold weather (interaction of compounding and cascading risk).

A list of the damages that occurred to the infrastructures of the area affected by the Hurricane is outlined by the New York City Government report "*PlaNYC*: A Stronger, More Resilient New York," [28] as well as other supporting damage data provided by the research published in [34], [33], and [35], among others. Moreover, for the purposes of their research, Haraguchi and Kim [36] summarize a list of the damages provided by the New York City Government. Table 1 is adapted based on their findings.

Table 1. Direct and indirect damage in each sector

Sector	Direct Damage	Indirect Damage
Building	Physical damage	Loss of utility, access to transportation, water, waste water, waste
Food	Physical damages to facilities	Stopped operations due to electrical outage, the lack of access to water, transportation
Liquid Fuel	Physical damages to refineries, pipelines, gas stations	Stopped operations due to electrical outage, the lack of access to water, waste water, transportation, and licensing issues
Healthcare	Physical damages to buildings	Stopped operations due to electrical outage, the lack of access to water, waste water, transportation
Telecommunication	Physical damages to facilities	Stopped operations due to electrical outage
Transportation	Physical damages to tunnels, subway lines, closure of bridges	Stopped operations due to electrical outage and lack of fuels
Utility	Physical damages to substations, distributions and transmission lines	Preemptive closure, lack of supply from New Jersey, adjustment due to the overload
Water and Waste Water	Physical damages to facilities	Stopped operations due to electrical outage
Waste	Physical damages to facilities and trucks	Stopped operations due to electrical outage

They distinguish the damage that occurred to the critical infrastructure sectors as direct and indirect damages. Direct damages are defined as the "physical damages caused by Sandy in each sector," whereas indirect damages are those "caused by functional problems such as power outage, overload, and impacts of failures in other sectors." As shown in Table 1, direct damages are mostly physical damages to sector facilities while indirect damages can be attributed to the effects that these physical damages induce on the other sectors.

The damage analysis confirms the high degree of interdependency existing among the CI sectors, meaning that each one of them strongly rely on the services and the outputs provided by other connected systems. As highlighted by Haraguchi and Kim [36], this interconnectedness determines the several indirect damages triggered by a sector that falls onto the others. In fact, as these systems are highly interconnected, the consequences of disruptions may propagate widely [10]. Because of this interconnectedness, several cascading effects on the networked sectors of the area have been reported. For example, as reported by Flegenheimer [37], power outages limited efforts for the restoration of subway service, since running a test train in the subway system could not start until power had been restored to the path of the test train. As also confirmed by the New York City Government [28], power outages contributed to the overall transportation network shutdown, as well as to the inoperability of liquid fuel facilities. Moreover, the deployment of utility restoration crews and emergency vehicles to areas in need was delayed by damage that occurred to the transportation infrastructures and by fuel disruption. In addition, buildings, hospitals and other healthcare centers had to be evacuated due to power outages, the lack of fuel, and the failure of emergency backup generators. This lack of preparedness led to further indirect damages and problems with the entire network. For example, long lines and consequent traffic congestion were reported in the proximity of gas stations that still had power to pump fuel, therefore the disruption of the utilities sector affected both the liquid fuel and the transportation sectors at the same time. Moreover, damaged streets hindered utility efforts from reaching and repairing the damage to impacted facilities that provide power to streets and buildings, thus the damage to transportation infrastructures affected both the utilities and buildings sectors. Overall, as also confirmed by Haraguchi and Kim [36] in Table 1, we can affirm that the power sector indirectly affected practically all of the other sectors in the network, especially the transportation, liquid fuel, telecommunication, and healthcare sectors, and therefore it can be considered as the most critical infrastructure among the others.

Several initiatives can be implemented to increase the community resilience of a region affected by an extremely disruptive event to increase its ability to withstand and recover from similar future events [38-41]. In December 2012, immediately after Hurricane Sandy, the New York City Government understood the need for a long-term plan to increase resiliency in the city's various infrastructures. It launched what is known as the Special Initiative for Rebuilding and Resiliency (SIRR), which produced a plan of strategies to adopt in order to strengthen the protection of New York's infrastructures, buildings, and communities against the impacts of future climate risks, published in the New York City Government report [28]. Among the more than 200 initiatives outlined, our attention is focused on analyzing those concerning the utilities, liquid fuel, and transportation sectors. Based on the damage analysis, these were the sectors most directly damaged by the storm and, as confirmed by Table 1, caused the majority of indirect damages because of their interconnection with other infrastructures. They can also be considered as the key sectors in the overall infrastructure network, due to the strong dependency of the other sectors on them and also because of high concentration of their facilities in the area under analysis, from refineries to power plants and a dense transportation system. Based on some assumptions, the initiatives proposed for these sectors can be organized according to the results provided by the IIM.

3.2 Application of the Methodology to the Case Study

The regional demand-reduction IIM is applied for the evaluation of the degree of interdependency among economic industries or critical infrastructure sectors in the portion of the metropolitan area of New York that has been identified.

The 2012 “make” and “use” matrices needed to run the IIM have been downloaded from the BEA website as Hurricane Sandy hit in October 2012. The RIMS II multipliers have also been purchased for the region of interest (Figure 2), consisting of counties covering the five boroughs of the city of New York (Bronx, Kings, New York, Queens, and Richmond) and the counties of the state of New Jersey that fall into its metropolitan area (Bergen, Essex, Hudson, Hunterdon, Mercer, Middlesex, Monmouth, Morris, Ocean, Passaic, Somerset, Sussex, Union). Despite the fact that they refer to 2013 regional data, they can be used for the regional decomposition of 2012 national data since they do not vary much in a year, thus the relation among infrastructures practically stays the same. They are presented as Tables in which every column identifies the sector whose demand reduction affects the sectors along the rows. For the purpose of this analysis, the multipliers referring to the column sectors named ‘utilities’, ‘mining’, and ‘transportation’ are chosen. In these Tables, the multipliers are arranged according to a level of aggregation that does not correspond with the same structure of the make and use matrices, thus, on the basis of some assumptions, the original multipliers are manipulated and the adapted multipliers reported in Table 2 are considered.

Table 2. Adapted multipliers for regional decomposition

Code	**Industries**	**$\mathrm{li}_{\mathrm{utilities}}$**	**$\mathrm{li}_{\mathrm{tansp}}$**	**$\mathrm{li}_{\mathrm{mining}}$**
11	Agriculture, forestry, fishing, and hunting	0	0	0
21	Mining	0.0006	0.00015	1.002567
22	Utilities	1.0058	0.007488	0.007567
23	Construction	0.0135	0.008325	0.010867
31G	Manufacturing	0.0164	0.032513	0.020433
42	Wholesale trade	0.014	0.031438	0.017433
44RT	Retail trade	0.0034	0.005925	0.001933
48TW	Transportation and warehousing	0.0294	1.0778	0.009467
51	Information	0.0121	0.0184	0.0102
FIRE	Finance, insurance, real estate, rental, and leasing	0.0709	0.1215	0.0564
PROF	Professional and business services (includes waste management)	0.0514	0.044425	0.036367
6	Educational services, health care, and social assistance	0.0009	0.000850	0.0007
7	Arts, entertainment, recreation, accommodation, and food services	0.0093	0.006425	0.003967
81	Other services, except government	0.0102	0.010125	0.002833
G	Government	0.008903	0.020372	0.000262

Three types of interdependency matrices are calculated for the application of the model. The first matrix is the national interdependency matrix A (Table 3), obtained by Equation 7 from the combination of the normalized “make” and “use” matrices.

Table 3. Interdependency matrix

10Code	Industries/Industries	11	21	22	23	31G	42	44RT	48TW	51	FIRE	PROF	6	7	81	G
	Name	Agriculture	Mining	Utilities	Construction	Manufacturing	Wholesale trade	Retail trade	Transportation	Information	Finance, insurance	Profession	Education	Arts, entertainment	Other services	Government
11	Agriculture, forestry, fishing, and hunting	2.18E-01	2.56E-04	8.25E-06	1.59E-03	4.74E-02	3.11E-05	1.25E-03	9.44E-05	4.15E-05	1.85E-05	6.14E-04	3.46E-04	5.74E-03	1.11E-04	1.09E-03
21	Mining	6.66E-03	7.68E-02	7.51E-02	9.46E-03	1.04E-01	1.71E-04	2.13E-04	3.06E-03	5.22E-04	8.00E-04	6.57E-04	5.95E-04	1.79E-03	1.23E-03	5.43E-03
22	Utilities	7.40E-03	4.30E-03	4.45E-03	1.41E-03	7.72E-03	2.64E-03	6.36E-03	4.51E-03	2.47E-03	9.82E-03	2.28E-03	7.42E-03	8.09E-03	3.66E-03	6.28E-03
23	Construction	5.79E-03	8.63E-03	1.59E-02	1.37E-04	2.93E-03	1.13E-03	2.27E-03	4.46E-03	2.14E-03	2.43E-02	6.47E-04	1.13E-03	2.77E-03	5.00E-03	2.10E-02
31G	Manufacturing	1.97E-01	8.18E-02	6.11E-02	2.30E-01	3.41E-01	2.75E-02	3.07E-02	1.84E-01	7.36E-02	1.00E-02	4.53E-02	8.40E-02	1.30E-01	9.25E-02	1.16E-01
42	Wholesale trade	5.26E-02	1.27E-02	1.04E-02	3.74E-02	4.84E-02	2.51E-02	1.56E-02	3.23E-02	1.78E-02	2.91E-03	7.05E-03	1.78E-02	2.09E-02	1.41E-02	1.34E-02
44RT	Retail trade	4.41E-04	4.24E-04	6.63E-04	6.37E-02	2.33E-03	3.23E-04	3.66E-03	4.67E-03	2.82E-04	1.03E-03	6.81E-04	6.40E-04	6.22E-03	9.41E-03	6.84E-05
48TW	Transportation and warehousing	2.86E-02	1.86E-02	3.72E-02	1.58E-02	2.44E-02	4.00E-02	4.73E-02	1.06E-01	1.41E-02	4.69E-03	1.35E-02	1.02E-02	1.26E-02	7.99E-03	1.83E-02
51	Information	1.68E-03	4.05E-03	4.60E-03	4.91E-03	7.21E-03	1.75E-02	1.91E-02	8.57E-03	1.61E-01	1.40E-02	2.85E-02	1.81E-02	1.39E-02	1.53E-02	2.89E-02
FIRE	Finance, insurance, real estate, rental, and leasing	4.43E-02	2.66E-02	2.11E-02	2.40E-02	1.30E-02	6.57E-02	1.02E-01	7.07E-02	4.74E-02	1.63E-01	7.36E-02	1.24E-01	8.18E-02	1.19E-01	2.84E-02
PROF	Professional and business services	1.07E-02	4.74E-02	4.15E-02	3.00E-02	6.03E-02	1.20E-01	1.06E-01	5.75E-02	9.99E-02	7.10E-02	1.50E-01	9.58E-02	1.08E-01	5.70E-02	7.65E-02
6	Educational services, health care, and social assistance	8.50E-04	0.00E+00	2.27E-04	1.31E-05	1.26E-05	6.87E-04	5.45E-03	7.46E-05	5.72E-04	6.99E-06	2.01E-04	1.09E-02	1.36E-03	2.72E-03	8.59E-03
7	Arts, entertainment, recreation, accommodation, and food services	1.21E-03	1.67E-03	4.88E-03	1.74E-03	3.46E-03	5.51E-03	4.17E-03	3.29E-03	2.43E-02	7.95E-03	1.80E-02	1.31E-02	2.30E-02	5.20E-03	9.32E-03
81	Other services, except government	2.32E-03	1.14E-03	1.90E-03	3.88E-03	2.95E-03	1.22E-02	8.52E-03	4.76E-03	9.18E-03	5.43E-03	9.69E-03	1.31E-02	1.03E-02	9.09E-03	7.75E-03
G	Government	6.30E-03	4.14E-03	6.31E-03	4.17E-03	9.09E-03	1.32E-02	1.18E-02	3.73E-02	1.53E-02	1.41E-02	8.29E-03	9.32E-03	1.33E-02	9.18E-03	1.31E-02

Then, the regional interdependency matrix A^R is calculated by considering each column of the adapted multipliers (Table 2) and implementing them in Equation 9. A single matrix A^R is calculated for each of the three different sectors considered, therefore defining a relationship among the interconnected systems that changes and adapts itself according to the sector that is subjected to demand reduction. Finally, three regional demand-side interdependency matrices A^{*R} are calculated according to Equation 16 as a function of the ratio between the total industry regional outputs of two industries. The regional production outputs referring to the region of interest are evaluated proportionally to the national outputs by calculating the following ratio between the U.S. GDP and the combined GDP relative to New York City and New Jersey:

- GDP U.S. (2012) = 14,530,716 million dollars
- GDP N.Y.C.+N.J. (2012) = 1,446,659 million dollars
- GDP N.Y.C.+N.J. / GDP U.S. :o; 0.1 (1/10)

Finally, the model is applied to evaluate the rankings of the most affected sectors in terms of inoperability caused by a functionality reduction in ‘utilities’, ‘mining’, and ‘transportation’ sectors. Figure 3 reports the results obtained for a 10% trial input of their functionality reduction. In fact, the order of the ranking obtained does not change for an increase/decrease of this value, since the output values change proportionally to the input, thus a trial value can be considered representing this ranking of inoperability graphically.

Figure 3

The inoperability rankings do not show the inoperability of the sectors subjected to reduction of functionality since they are an order of magnitude higher than the others, so as to allow a better visibility of the latter. The specific sector inoperability does not have a unique value but it changes in value and in position in the rankings according to the sector whose functionality is perturbed. Despite the model validity and due to its limitations, it is not able to "catch" some interdependencies. For example, surprisingly, the inoperability of the health care sector appears only at the bottom of all of the rankings, seeming as if the demand reduction on the three sectors does not influence the health care sector much. This can only mean that the sector does not strongly depend on the others and, as confirmed by the evidence, it has a high ability to isolate itself as it appears in emergency situations especially. Also, the disruption to utilities generates an inoperability of the mining sector that is one order bigger than the others, while the other disruption causes inoperability comparable to each other.

A correspondence among the industries of the economic data and the critical infrastructure sectors is needed. Table 4 shows this correspondence, which assumes that the same interaction among the economic industry sectors can be identified in the network of critical infrastructure sectors. As seen, there is not a perfect correspondence among them and some of the industries in the economic data can be identified with more than one critical infrastructure sector defined in the New York City Government report (in **bold**) [28]. Some correspondences may also seem excessive, such as "Professional and business services," which corresponds to solid waste, water, and wastewater management services, since this economic industry sector includes these services.

Table 4. Correspondence between BEA industries and critical infrastructure sectors

Code	**Industries**	**Critical infrastructure sectors**
11	Agriculture, forestry, fishing, and hunting	Food and Agriculture
21	Mining	Liquid Fuels
22	Utilities	Utilities
23	Construction	Buildings
31G	Manufacturing	Critical Manufacturing
42	Wholesale trade	Commercial Facilities
44RT	Retail trade	Commercial Facilities
48TW	Transportation and warehousing	Transportation
51	Information	Communications
FIRE	Finance, insurance, real estate, rental, and leasing	Financial Services
PROF	Professional and business services*	Solid Waste, Water and Wastewater
6	Educational services, health care, and social assistance	Healthcare and Public Health
7	Arts, entertainment, recreation, accommodation, and food service	Commercial Facilities
81	Other services, except government	Emergencies Services
G	Government	Government Facilities

Also, the original definition (in *italic*) given by the Department of Homeland Security (DHS) is considered when no correspondence is found, such as in the case of manufacturing, wholesale and retail trade, and government sectors that, among others, do not appear in the New York City Government report [28]. For the purpose of this analysis, these correspondences are however assumed and provide satisfying results.

Table 5, Table 6, and Table 7 report the new inoperability calculated using Equation 17. These inoperabilities correspond to increasing percentages of perturbation to the three sectors under analysis, which now, after the supposed correspondence in Table 4, are ‘utilities,’ ‘liquid fuel,’ and ‘transportation’.

Table 5. New percentages of inoperability due to functionality reduction in *utilities sector*

% INOPERABILITY FOR SECTORS

	Transportation	Critical Manufacturing	Commercial Facilities	Solid Waste, Water and Wastewater	Financial Services	Utilities	Government Facilities	Emergencies Services	Liquid Fuels	Communications	Buildings	Food and Agriculture	Healthcare and Public Health
% FUNCTIONALITY REDUCTION OF UTILITIES SECTOR	10.00	5.87	1.65	0.60	0.54	0.47	0.32	0.19	0.15	0.12	0.09	0.01	0.00
	20.00	11.74	3.29	1.19	1.09	0.93	0.64	0.39	0.30	0.23	0.17	0.01	0.01
	30.00	17.61	4.94	1.79	1.63	1.40	0.97	0.58	0.45	0.35	0.26	0.02	0.01
	40.00	23.48	6.59	2.38	2.18	1.86	1.29	0.77	0.60	0.46	0.34	0.02	0.02
	50.00	29.35	8.23	2.98	2.72	2.33	1.61	0.96	0.76	0.58	0.43	0.03	0.02
	60.00	35.22	9.88	3.57	3.27	2.80	1.93	1.16	0.91	0.69	0.51	0.03	0.03
	70.00	41.09	11.53	4.17	3.81	3.26	2.26	1.35	1.06	0.81	0.60	0.04	0.03
	80.00	46.96	13.17	4.76	4.36	3.73	2.58	1.54	1.21	0.92	0.69	0.04	0.04
	90.00	52.83	14.82	5.36	4.90	4.20	2.90	1.73	1.36	1.04	0.77	0.05	0.04
	100.00	58.70	16.46	5.95	5.45	4.66	3.22	1.93	1.51	1.15	0.86	0.06	0.05

Table 6. New percentages of inoperability due to functionality reduction in *transportation sector*

	% INOPERABILITY FOR SECTORS												
	Transportation	Critical Manufacturing	Commercial Facilities	Solid Waste, Water and Wastewater	Financial Services	Utilities	Government Facilities	Emergencies Services	Liquid Fuels	Communications	Buildings	Food and Agriculture	Healthcare and Public Health
% FUNCTIONALITY REDUCTION OF TRANSPORTATION SECTOR	10	2.36	1.68	1.29	1.09	0.93	0.84	0.49	0.49	0.48	0.30	0.06	0.00
	20	4.73	3.36	2.57	2.17	1.85	1.69	0.97	0.97	0.96	0.59	0.12	0.01
	30	7.09	5.05	3.86	3.26	2.78	2.53	1.46	1.46	1.44	0.89	0.19	0.01
	40	9.45	6.73	5.14	4.35	3.71	3.38	1.95	1.94	1.91	1.18	0.25	0.01
	50	11.81	8.41	6.43	5.44	4.64	4.22	2.43	2.43	2.39	1.48	0.31	0.01
	60	14.18	10.09	7.71	6.52	5.56	5.06	2.92	2.92	2.87	1.77	0.37	0.02
	70	16.54	11.78	9.00	7.61	6.49	5.91	3.40	3.40	3.35	2.07	0.43	0.02
	80	18.90	13.46	10.28	8.70	7.42	6.75	3.89	3.89	3.83	2.36	0.50	0.02
	90	21.27	15.14	11.57	9.78	8.34	7.60	4.38	4.37	4.31	2.66	0.56	0.02
	100	23.63	16.82	12.86	10.87	9.27	8.44	4.86	4.86	4.78	2.96	0.62	0.03

Table 7. New percentages of inoperability due to functionality reduction in *liquid fuel sector*

% INOPERABILITY FOR SECTORS

	Transportation	Critical Manufacturing	Commercial Facilities	Solid Waste, Water and Wastewater	Financial Services	Utilities	Government Facilities	Emergencies Services	Liquid Fuels	Communications	Buildings	Food and Agriculture	Healthcare and Public Health
% FUNCTIONALITY REDUCTION OF LIQUID FUEL SECTOR	10	2.15	1.63	1.62	1.34	1.03	0.85	0.63	0.35	0.18	0.15	0.08	0.00
	20	4.30	3.25	3.24	2.68	2.05	1.69	1.26	0.69	0.36	0.29	0.17	0.00
	30	6.45	4.88	4.86	4.02	3.08	2.54	1.89	1.04	0.54	0.44	0.25	0.00
	40	8.60	6.51	6.48	5.36	4.10	3.39	2.52	1.39	0.73	0.59	0.34	0.00
	50	10.76	8.14	8.10	6.70	5.13	4.23	3.15	1.73	0.91	0.73	0.42	0.00
	60	12.91	9.76	9.73	8.04	6.15	5.08	3.78	2.08	1.09	0.88	0.51	0.00
	70	15.06	11.39	11.35	9.38	7.18	5.93	4.40	2.43	1.27	1.03	0.59	0.00
	80	17.21	13.02	12.97	10.72	8.20	6.77	5.03	2.77	1.45	1.17	0.67	0.00
	90	19.36	14.65	14.59	12.06	9.23	7.62	5.66	3.12	1.63	1.32	0.76	0.00
	100	21.51	16.27	16.21	13.40	10.25	8.47	6.29	3.47	1.82	1.47	0.84	0.00

Figure 4 compares the inoperability ranking obtained for 10% functionality reduction of utilities sector before and after the values are scaled using Equation 17. These scaled values now define a meaningful inoperability that can be compared to that of the perturbed sector and are representative of reality.

Figure 4

Table 8 shows the inoperability ratios calculated using Equation 18 for functionality reductions occurring singularly to each of the three sectors on which this paper focuses, which, after the correspondence in Table 4, are ‘utilities,’ ‘transportation,’ and ‘liquid fuel.’

Table 8. Inoperability ratios for functionality reductions of utilities, transportation, and liquid fuel sectors

	UTILITIES	**TRANSPORTATION**	**LIQUID FUEL**
UTILITIES	α %	0.16 α %	0.59 α %
TRANSPORTATION	0.09 β %	β %	0.05 β %
LIQUID FUEL	0.13 γ %	0.22 γ %	γ %

The sectors along the rows are the sectors subjected to a functionality reduction or perturbation due to the extreme events. The sectors along the columns are the impacted sectors whose inoperability is caused both by the perturbation to the row sectors and due to the interconnections. These values can be used as indicators to understand how the sectors affected each other and the amount of inoperability that is induced to the sectors of the network as a consequence of the degree of dependency and interconnection with the one perturbed.

The effect on itself of the functionality reduction occurred to a sector is always equal to the maximum, defined by α%, β%, and γ%, respectively, for the utilities, transportation, and liquid fuel sectors. The impact on the others has non-mutual variable values: the inoperability of one sector induced by functionality reduction occurring to another sector is not the same of the inoperability of this last sector induced by the first one. For example, in the case of a functionality reduction to the utilities sector, the liquid fuel sector is the most impacted with an inoperability always equal to 59% of that of the utilities sector, corresponding to an inoperability ratio of 0.59 α%. On the other hand, the inoperability of the utilities sector induced by a functionality reduction to the liquid fuel sector is always 13% (0.13 γ%) of that of the liquid fuel sector. The same considerations can be made by analyzing the impact of the utilities disruption on the transportation sector (0.16 α%) and vice versa (0.09 β%), as well as the impact of the transportation disruption on liquid fuel sector (0.05 β%), and vice versa (0.22 γ%). Overall, it is possible to explain these percentages and their lack of reciprocity by considering the dependencies among sectors during normal conditions and the way each sector affects the others when a disruption occurs. Both at the community and company levels, several examples can be reported to support the previous percentages, showing how each sector's inoperability affected the others and how a single occurrence led to multiple consequences in the circumstances of Hurricane Sandy. For example, power outages caused disruptions and issues at every stage of the fuel supply chain. Refineries and pipelines in the area that were forced to close or reduce their operations because of no power to run their facilities, while maritime terminal and gas stations were suspended or had limited operations because of disruptions in power supply or limited operations using backup generators. Fuel could not be discharged from tankers and loaded into storage tanks and, as a consequence of the damage to the electrical systems, this also reduced the ability to dispense fuel to delivery trucks and caused the closure of several gas stations because of the depletion of previous fuel supplies. On the other hand, the impact on the utilities sector of the disruptions occurring to the liquid fuel sector was smaller. The fuel shortage limited the use of power and steam generation plants, which, in the case of natural gas disruption, preemptively must switch to fuel, as well as the possibility to run backup electric generators as alternative sources of power for more and less critical users. It also delayed utility restoration efforts by making it more difficult to refuel power restoration crews. Many other examples can be identified in order to support the other four inoperability ratios previously defined. Table 9 can also be used to analyze disruptions in two sectors, for example, the effects of disruptions on utilities (power supply) and fuel supply on transportation as 0.16 α%+0.22 γ%. During Hurricane Sandy, power supply created a fuel supply scarcity that prevented transportation agencies from inspecting bridges immediately after the hurricane. This, in turn, delayed the supply of liquid fuel to gas stations, resulting in an artificial crisis of fuel shortages. Long lines at fewer gas stations with fuel could be seen for almost 8-10 days after the hurricane because of this interdependency of these three infrastructures.

The percentages in Table 9 are used to select and rank the priority initiatives among many that can be implemented. In particular, a policymaker should focus on initiatives that can reduce the inoperability ratios between different sectors to values as close to zero as possible. There is urgent need to focus on this selection of initiatives mainly for two reasons: as reported by the damage analysis, indirect damage is not negligible; the induced inoperability is a considerable component of the overall inoperability of one sector. A reduction of the inoperability ratios corresponds to an increase of the sector independence, as well as to a reduction of its chance of being influenced by a problem affecting another sector. Several initiatives can reduce these values by reducing the influence that damage occurring to one sector has on the others, corresponding to a reduction of induced inoperability. The entire list of initiatives are grouped in different tables in Crupi's master thesis [42], while due to the lack of space only two of these tables (Table 9 and 10) will be explained below.

They are organized by distinguishing the cause of the induced inoperability, relative to something that happened to the perturbed sector, the effect of this cause, which is described as a problem or damage characterizing the impacted sector, and the specific initiative proposed to solve it. In some cases, more than one initiative can be considered to reduce the effect induced by a specific problem. In the cases in which a high percentage of inoperability ratio is obtained, it was possible to define more initiatives to help reduce it; whereas where these values are low, and therefore the induced inoperability also has a low value, a reduced number of initiatives were identified. Finally, some initiatives can be considered to reduce more than one induced inoperability, especially in the cases where multiple reasons led to a common problem, for example, inoperability in the transportation sector because of disruptions in both utilities and liquid fuel sectors.

Table 9. Initiatives proposed for the *liquid fuel sector* to reduce the effects caused by a reduction of functionalities in the *utilities sector*

PRIMARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF UTILITIES		
UTILITIES **α%**	**LIQUID FUEL** **0.59 α%**	
Causes	**Effects**	**Initiatives**
Power outage No functioning backup generators	Shutdown of refineries and pipelines or reduction of their operation	1: Develop a fuel infrastructure hardening strategy
Power outage Damage to terminals electric equipment	Shutdown of terminals or reduction of their operation, impossibility to discharge fuel tankers	6: Creation of a transportation fuel reserve
Power outage No possibility to fast connect to backup generators	Closure of gas stations	5: Ensure that a subset of gas stations and terminals have access to backup generators in case of widespread power outages

Lack of planning of backup generator prepositioning	Closure of gas stations	4: Provision of incentives for the hardening of gas stations
Damage to electric systems and equipment	Bottlenecks along pipelines and delays in fuel supply	3: Build pipeline booster stations in New York City
Damage to fuel facilities electric equipment	Reduction of capacity to dispense fuel to delivery trucks	8: Development of a package of City, State, and Federal regulatory actions to address liquid fuel shortages during emergencies

Table 9 explains how the damages and outages on the utilities sector affect the liquid fuel sector and list some initiatives useful to recover from the corresponding inoperability. For example, Sandy caused disruptions at nearly every level of the fuel supply chain, reducing the fuel flow in the New York metropolitan area. Most of the infrastructures affected were located in New Jersey, where a combination of extended power outages and direct damages from the storm surge, nearly dried up New York City's fuel supply. For three consecutive days after Sandy, all fuel terminals in the New York metropolitan area were completely out of service, while one week after only 20 percent of the pump stations recover and could distribute fuel. To overcome the emergency the Federal Government has developed in New Jersey a fuel infrastructure hardening strategy with the goal of increasing the resilience of the transportation network.

To face the shutdown of terminals or the reduction of their operation, the City explored the creation of a transportation fuel reserve to temporarily supply the private market during disruptions. Even if the fuel supply chain is hardened, the possibility of widespread disruption to supply still exists. The City worked with Federal and State Governments to evaluate the feasibility and cost of such a program. Such a program would complement the already existing Northeast Home Heating Oil Reserve, managed by the US DOE in Connecticut. Power outages caused also the closure of gas stations: to cope with this situation the City ensured that a subset of gas stations and terminals have access to backup generators in case of widespread power outages, creating a pre-event positioning plan to enable the ready deployment of generators to impact areas immediately in the wake of a disaster. The closure of gas station was also caused by the lack of planning of backup generator prepositioning. Therefore, the New York State worked to provide incentives for the hardening of gas stations to withstand extreme weather events. Although lack of power supply at gas stations was not the primary cause of fuel shortages after Sandy, a widespread power outage in the city would cripple gas station operations, making gasoline and diesel unavailable. New York State's 2013–2014 budget requires retail fuel stations within a half-mile of controlled access roads and designated evacuation routes to invest in equipment that would allow them to connect generators quickly in the event of a power loss, and to enter into supply contracts for emergency generators. The damage on the electric system and on the fuel facilities electric equipment caused delay in fuel supply and a reduction of capacity to dispense fuel to delivery trucks. For the first the New York State worked to safely build pipeline booster stations in New York City to increase supply and withstand extreme weather event: these booster station increased supply during shortages. For the second the

City, the State and Federal Government worked together to develop regulatory actions to address liquid fuel shortages during emergencies. The waiver of the Jones Act, for example, would allow foreign-flagged ships to deliver fuel into the region. Waivers of the City's fuel sulfur requirements and the local formulation requirements would allow fuel that is normally consumed upstate and elsewhere to be shipped into and sold within New York City. A waiver of the on-road diesel fuel requirement would allow heating fuel to be used in vehicles. The imposition of fuel rationing would further allow the retail fuel supply to stabilize.

Table 10 explains the effects on the transportation sector caused by damage and outages on the utilities sector and displays some initiatives useful to recover from inoperability. Sandy had a massive impact on the transportation system within New York City and the surrounding region, with the greatest impact felt on those elements located underground and close to the shoreline. The storm caused extensive damage and impaired the ability of the system to move people in and around the city and region. Beyond the immediate impact of flooding, power outages from Sandy severely affected the transportation system. Lack of power meant that key equipment could not operate (e.g., train lines and tunnel ventilation equipment dependent on electricity). It also was a major impediment to the dewatering of the major tunnel infrastructure.

Table 10. Initiatives proposed for the *transportation sector* to reduce the effects caused by a reduction of functionalities in the *utilities sector*

SECONDARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF UTILITIES		
UTILITIES α%	**TRANSPORTATION 0.16 α%**	
Causes	**Effects**	**Initiatives**
Power outage	No functioning traffic signals	3:Elevation of traffic signals and provision of backup electrical power
Damage to overhead power lines torn down by tree branches and/or wind	Closure of streets	6:Hardening of vulnerable overhead lines against winds
Power outage Damage to tunnel electrical equipment and control systems	Closure of road and rail tunnels	4:Protection of NYCDOT tunnels from flooding
Power outage Damage to bridges' electrical equipment and control systems	Inoperability of moveable bridges	5:Installation of watertight barriers for mechanical equipment of bridges
Repair or replacement of old and damaged subway electric equipment	Delayed restoration of subway service	1: Develop a cost-effective upgrade plan of utilities systems

Power outage Inoperable key electric equipment	Suspension of train and subway services, overwhelming of other transportation systems that do not rely on power lines, and more private vehicles traffic	9: Planning for temporary transit services in the event of subway system suspensions 12: Planning and installation of new pedestrian and bicycle facilities 14: Deployment of the Staten Island Ferry's Austen Class vessels on the East River Ferry and during transportation disruptions 16: Expansion of the city's Select Bus Service network 18: Expansion of ferry services in locations citywide 11: Implementation of High-Occupancy Vehicle (HOV) requirements

Climate change could have a significant impact on the city's transportation infrastructure, ranging from short-term outages to direct damage—or even destruction of critical assets, in some cases. Given the range of potential climate change impacts on the transportation network the City has implemented initiatives to protect the infrastructure from damage, outage and loss of service through protecting assets to maintain system operations. One of the initiatives assumed by the City provides for the elevation of traffic signals and provision of backup electrical power. Indeed New York's traffic signals are vulnerable to damage from flooding, as well as to power loss from various extreme weather events. Therefore, the City has raised controllers at approximately 500 intersections in flood-vulnerable locations, placing the electrical hardware above the 100-year flood elevation. In tandem with this effort, the City also will install power inverters in approximately 500 NYPD vehicles, which will allow these vehicles to provide backup electrical power to critical traffic signals if grid power is lost. Sandy caused also damage to tunnel electrical equipment and control system; for these reason road and rail tunnels were closed. Therefore, NYCDOT has evaluated a series of potential flood protection strategies, including installing floodgates and raising tunnel entrances and ventilation structures above flood elevations to provide specific protection for sensitive mechanical and electrical equipment, including ventilation, lighting, and safety systems. These works will end by 2020. Finally, Power outages caused also damage to bridges' electrical system that caused inoperability of moveable bridges. Subject to available funding, the City, through NYCDOT, will install watertight barriers to protect the bridges' mechanical equipment from flood damage to ensure that these critical crossings function properly.

On the basis of numeric values of the inoperability ratios, the selected initiatives can also be distinguished between primary and secondary initiatives, as reported in the header of each Table, so as to further prioritize them. Primary initiatives are those that would reduce the higher inoperability ratio; secondary initiatives would instead limit the lower inoperability ratio. Primary initiatives also refer to inoperability ratios that can be reduced more easily, since it can be assumed that it is easier to reduce a high value rather than a lower value.

The results of the method can therefore be used not only to define the ranking of the most inoperable sectors, but also to select the most priority initiatives to adopt in the aftermath of a disruptive event.

3.3 Actual recovery situation

In December 2012 was launched the Special Initiative for Rebuilding and Resiliency that convened to address the creation of a more resilient New York City in the wake of Hurricane Sandy, with a long-term focus on preparing for and protecting against the impacts of climate change. The result was the development by scores of City employees across variety of agencies of "A Stronger, More Resilient New York", a comprehensive plan that contains actionable recommendations both for rebuilding the communities impacted by Sandy and increasing the resilience of infrastructure and buildings citywide. The nearly $20 billion plan contained in this report includes over 250 initiatives. Together these initiatives will further protect the coastline as well as strengthen the buildings and all the vital systems that support the life of the city, including energy grid, transportation systems, parks, telecommunications networks, healthcare system, and water and food supplies. Table 11 shows some projects completed or in progress, which were implemented by the government of New York City in the aftermath of Sandy. These projects reflect the goals of the initiatives proposed in the document "A stronger more resilient New York".

Table 11. Some projects implemented by the New York City government for the post Sandy recovery.

PROJECT	COST [$ million]	WORK BEGINNING	END OF WORKS	INFRASTRUCTURE SECTOR	INITIATIVE
Rockaway Boardwalk	340	2014	2017	Transportation	12: Planning and installation of new pedestrian and bicycle facilities
South Ferry Station	369	2013	2017	Transportation	4: Protection of NYCDOT tunnels from flooding
Queens Mid Town Tunnel	237	2015	2019	Transportation	4: Protection of NYCDOT tunnels from flooding
NYC gas station (FUEL NY)	29	2013	-	Liquid fuel	1: Develop a fuel infrastructure

					hardening strategy 5: Ensure that a subset of gas stations and terminals have access to backup generators in case of widespread power outages
Build it back program	2200	2013	2017	(Other) Residential buildings	
BigU	335	2014	-	(Other) Coastal Protection	

PROJECT	**COST [$ million]**	**WORK BEGINNING**	**END OF WORKS**	**INFRASTRUCTURE SECTOR**	**INITIATIVE**
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NYC gas station (FUEL NY)	29	2013	-	Liquid fuel	1: Develop a fuel infrastructure hardening strategy 5: Ensure that a subset of gas stations and terminals have access to backup generators in case of widespread power outages
Build it back program	2200	2013	2017	(Other) Residential buildings	
BigU	335	2014	-	(Other) Coastal Protection	

3.4 Numerical results of the dynamic model

The effectiveness of these initiatives in the recovery phase following the event is studied through the application of the dynamic IIM. It is used to evaluate the recovery of the utilities sector and the benefits brought by the initiatives proposed for it, due to the availability of data regarding the power outages that affected the area under analysis for the days and weeks following the impact of the storm. This data corresponds to the percentage of customers in New Jersey and New York City that lost power due to Hurricane Sandy's impact on utility systems, which is calculated through the following steps: approximately 2.5 million customers were affected by power outages in New Jersey, corresponding to 62% of the total number of customers (source: [43]), which is equal to about 4.03 million customers; about 0.8 million customers lost power in New York City, out of a total 3.03 million customers (source: Con Edison, LIPA), thus representing 26 % of the total; around 3.3 million customers were without power in New Jersey and New York City in the wake of Sandy, out of a total of approximately 7.03 million customers, thus the percentage of power outages per customer in the area analyzed is equal to about 47%.

The 47% of customers affected by power outages represents the inoperability of the utilities sector at time 0, equal to the initial point of its recovery phase that can be described with the exponential law expressed by Equation 19. The sector recovery rate is expressed by Equation 20 assuming $q_i(T_i) = 1\%$ and $T_i = 30$ days.

Therefore, the recovery rate calculated with these values is k_i=0.1289*/day*. The first expression represents the residual inoperability of the utilities sector at the end of the recovery time T_i. Based on these values, the utilities sector achieves a 99% recovery in 30 days. Several authors, such as Lian and Haimes [19], consider this 1% residual inoperability in order to apply the dynamic model for the analysis of other catastrophic events, such as a terrorist attack on the infrastructure system. According to the information and Tables provided by the New York City government report, this 99% recovery rate in 30 days can be considered a reasonable value for the analysis of the recovery process because of power outages.

The results of the application of the dynamic IIM are shown in Figure 5 where is shown the behavior of the utilities sector before, during, and after the impact of Hurricane Sandy. This time-history is defined by the x-axis, in which time 0 corresponds to the impact and the perturbation induced by the storm. The y-axis instead represents the functionality of the sector which can be considered as the complement of inoperability.

Figure 5

The law governing the dynamic model represents the response of the sector due to the implementation of the initiatives for utilities. Their effectiveness influences the recovery time, thus the entire recovery phase. In fact, if these initiatives are not considered, a plausible assumption is that the recovery time is longer and more serious consequences are experienced by the sector and therefore by the community. On the other hand, recovery time is shorter if some of the initiatives proposed after Sandy's impact are already available for implementation in the event of its occurrence, improving the management of the emergency. This would lead to a higher recovery rate and an increase in overall resilience.

Overall, the results obtained appear to be realistic. In fact, according to what has been reported by the government of New York and by other sources, the efforts put in place for the recovery of the utilities sector drastically reduced its inoperability. The approximately 10% sector inoperability at 15 days after the event can therefore be considered as a plausible value.

3.5 Limitations of the model

The paper adopts an empirical model to examine a real situation that occurred and then employs realistic results, in terms of consequences of the event, to propose a way to prioritize recovery efforts after a disaster. The results obtained assuming a certain percentage of perturbation, due to the lack of specific data, highlight a certain linearity among perturbations and the affected sectors, which indeed does not necessarily occur because interdependencies among multiple sectors are not considered in the data provided by the Bureau of Economics. So, this limitation applies to the model, but it derives from the data source. Furthermore, it has been observed that the trend of the matrices provided by the Bureau of Economics does not change significantly after Hurricane Sandy, proving that the extreme event can be considered as a minor economic perturbation in a region which is one of the wealthiest in the US.

Another limitation of the model is that *qualitative factors* such as *Imageability, Enclosure, Human scale, Transparency* and *Complexity* ([44]; [45]) are not considered in the proposed model. These factors influence how an individual feel about the urban environment, so they should be part of the decision process while prioritizing different initiatives, therefore further exploration of this issues which are beyond the scope of this paper will be analyzed by the authors.

4. CONCLUDING REMARKS

Cascading effects and cascading disasters are emerging fields of scientific research. The widespread diffusion of functional networks increases the complexity of interdependent systems and their vulnerability to large-scale disruptions.

The aim of this study is to analyze the impact of Hurricane Sandy on the critical infrastructure sectors in the metropolitan area of New York. The Inoperability Input-Output model is used to gather and numerically define the interactions among these sectors based on economic data provided by the Bureau of Economic Analysis. The evaluation of the sectors' inoperability confirms the importance of utilities, liquid fuel, and transportation sectors in the network, as these were the most damaged sectors that caused cascading effects. In addition, in the aftermath of an event the proposed model can be used as a support tool that guides policymakers in the selection of the interventions that should be considered for the determination of an optimal restoration strategy. Results provided by the proposed model supports Pescaroli and Alexander's [7] findings on the importance of vulnerability in defining the cascading effects during a disaster and any future risk assessment at the community level.

The output of the model is a parameter called *inoperability ratio* that is defined as the percentage of inoperability that the perturbation in a sector causes on another one. In detail the parameter is calculated for perturbations affecting utilities, liquid fuel, and transportation sectors. For example, when the utilities and the transportation sectors are perturbed, the inoperability ratios are respectively 59% and 5% in the liquid fuel sector.

Priority initiatives that reduce the inoperability ratio between different sectors are recommended to be adopted to limit the induced inoperability produced by damage not directly affecting that sector. In fact, damage analysis shows that the indirect damage accounts for a significant component of the overall amount of damage experienced by a sector. Hence, attention should firstly be focusing on the initiatives that limit them. The advantage of the proposed model is the moderate data requirements and their ability to combine them with other analysis techniques. However, some limitations should be considered for the application of the model and the developments presented in this study. By using the IIM economic broad sectors is not possible to investigate all the potential consequences of an extreme disruptive event, such as Hurricane Sandy, in terms of loss of life and livelihood. For example, the analysis does not consider directly the structural damages of the CI systems, as well as the injuries and casualties that were reported. However structural damages are involved indirectly because they affect the different BEA industries sectors that are used as input of the model. Moreover, the extra-regional economic exchanges of the analyzed region are not considered as well as the interdependencies between infrastructures that belong to the same economic sector. Therefore, a possible development of this research could focus on the overcoming of these limitations, but additional data would be required to define the importance that each asset has in the overall sector.

5. ACKNOWLEDGEMENTS

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6. NOTATION

The following symbols are used in this paper:

A = technical coefficient interdependency matrix;

A^R = regional technical coefficient interdependency matrix;

A^* = demand-side technical coefficient interdependency matrix;

A^{*R} = demand-side regional technical coefficient interdependency matrix;

a_{ii}^* = diagonal element of the demand-reduction matrix;

a_{ij} = degree of dependency of each industry i from each industry j;

a_{ij}^R = degree of dependency of each regional industry i from each regional industry j;

c^* = demand-side perturbation vector;

k_i = industry resilience coefficient or interdependency recovery rate;

l = location quotients vector;

l_i = location quotient for the i^{th} industry;

ζ_{pj} = inoperability ratio;

q = demand-side inoperability vector;

$q_i(0)$ = inoperability of i sector at initial perturbation ($t = 0$);

$q_i(T_i)$ = inoperability of i sector at recovery time (T_i);

$q_i(t)$ = inoperability of i sector during the recovery phase for time $0 < t < T_i$;

q_j^R = original value of inoperability;

$q_{jscaled}^R$ = new value of induced inoperability;

q_p^R = inoperability of the sector affected by functionality reduction;

U = "use" matrix;

$\hat{U}$= normalized "use" matrix;

u_{ij} = monetary value of each commodity i consumed by each industry j;

$\hat{u}_{ij}$ = normalized monetary value of each commodity i consumed by each industry j;

V = "make" matrix;

$\hat{V}$= normalized "make" matrix;

v_{ij} = monetary value of each commodity j produced by each industry i;

$\hat{v}_{ij}$ = normalized monetary value of each commodity j produced by each industry i;

x^T = total industry input vector;

$\hat{x}_i$ = national output for the i^{th} industry;

$\hat{x}_s$ = total national output for all national-level industries.

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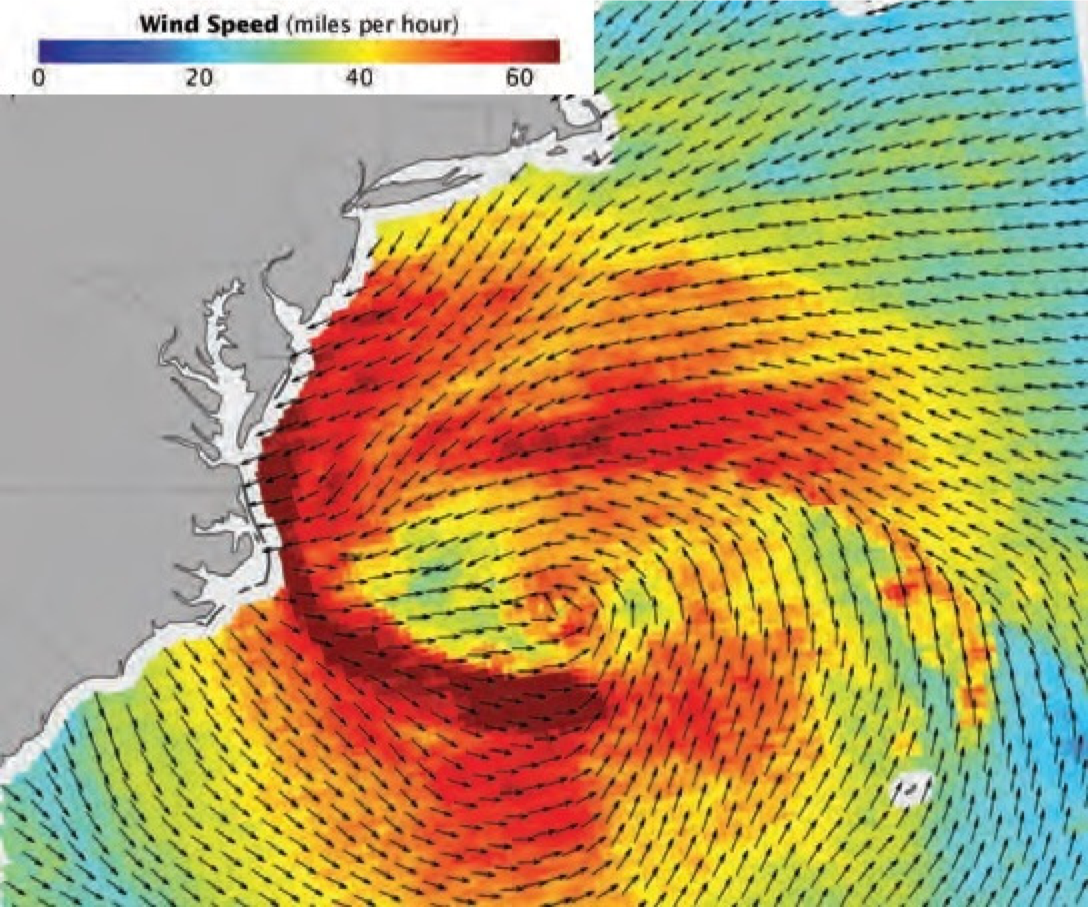
LIST OF FIGURES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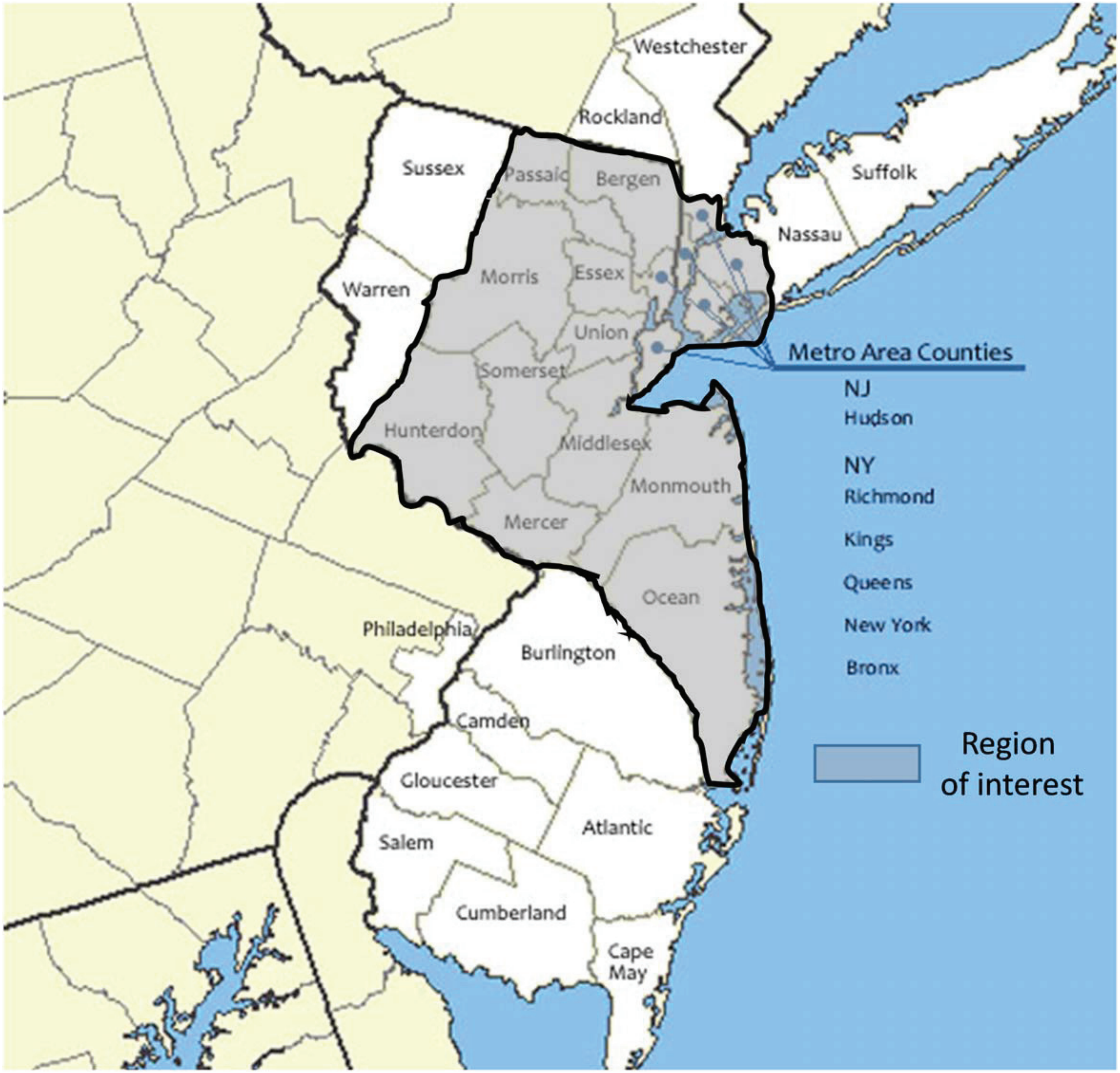
20
40
60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Mercer
Ocean
Philadelphia
Burlington
Camden
Gloucester
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Richmond
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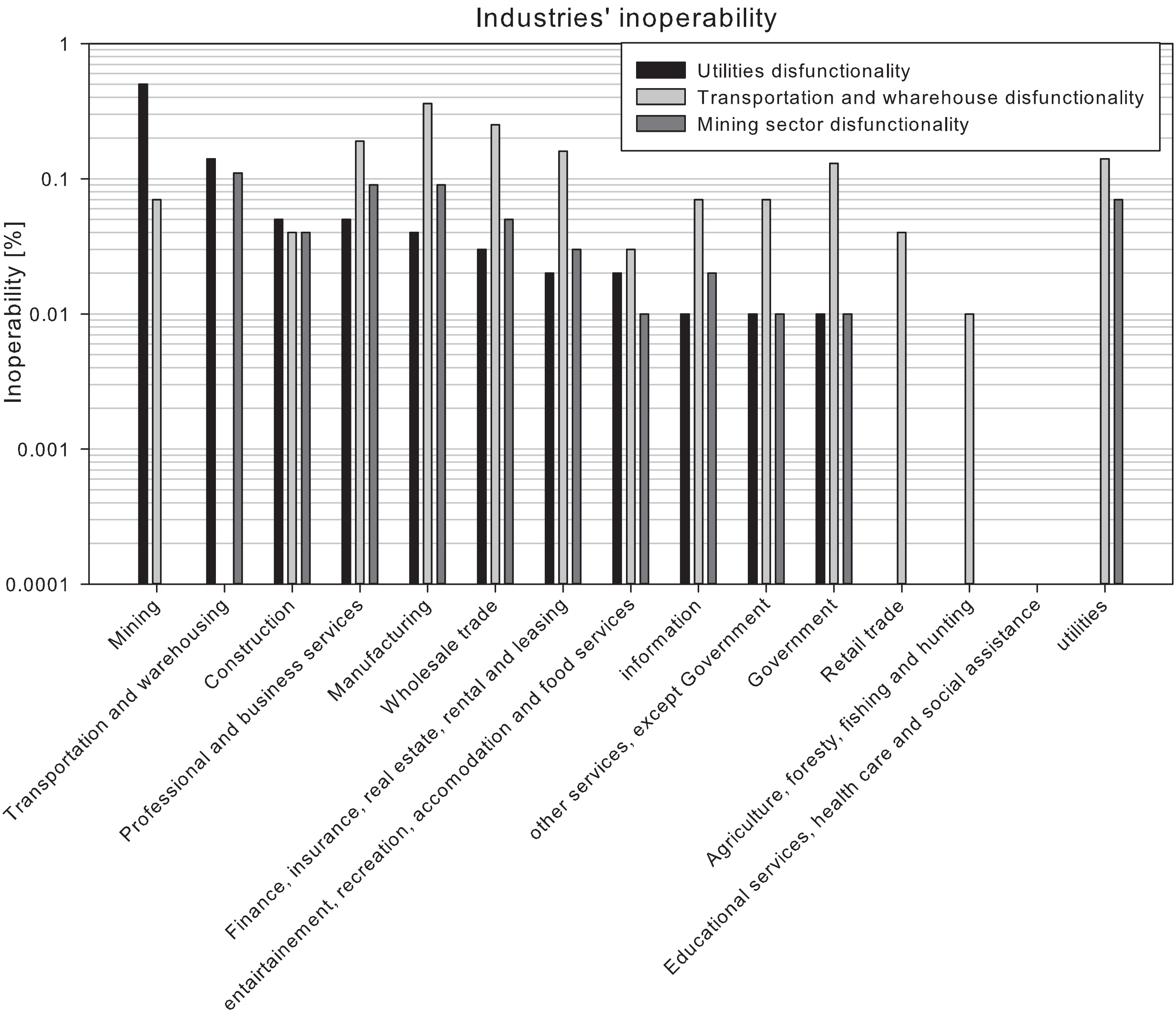
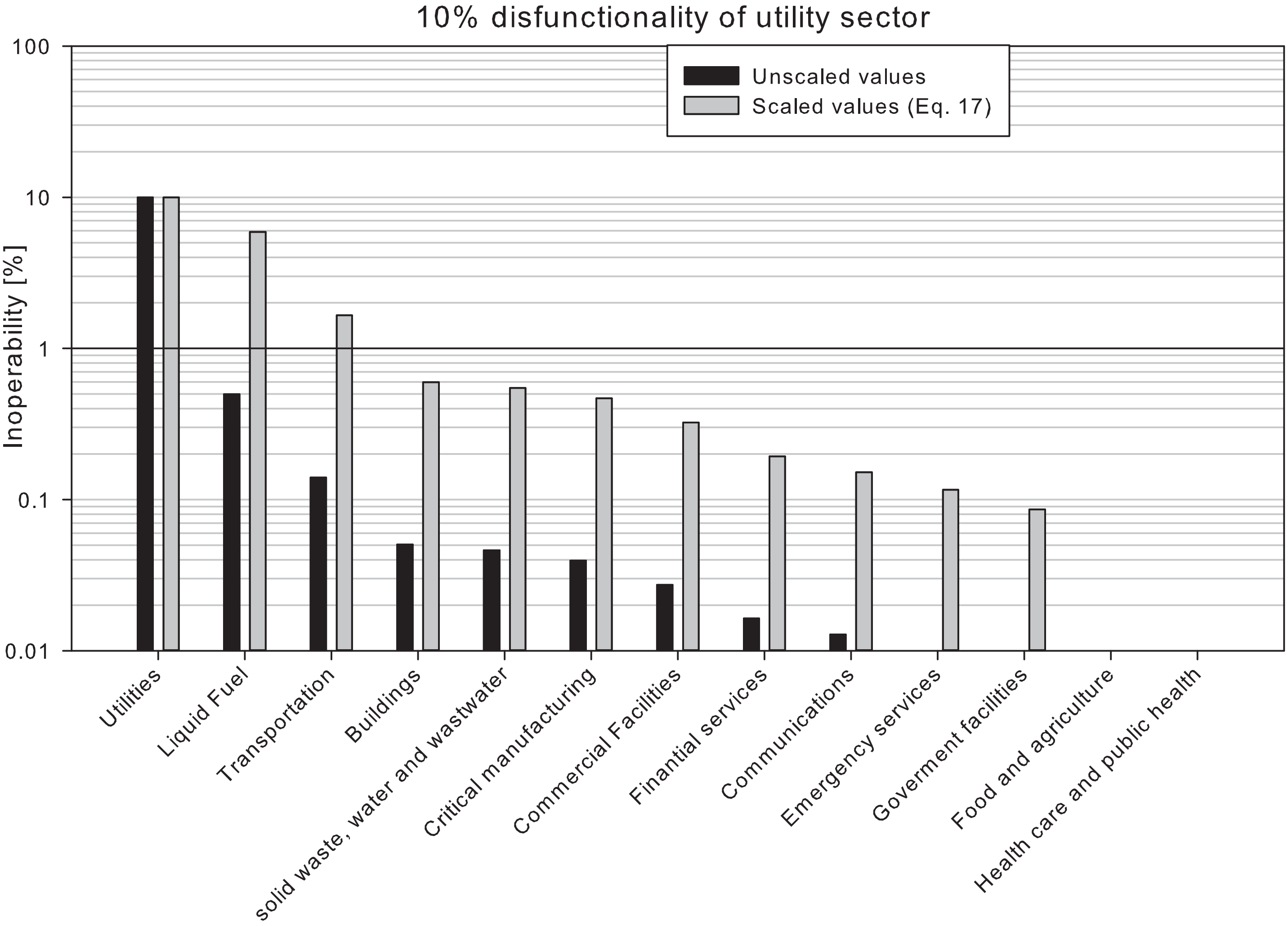
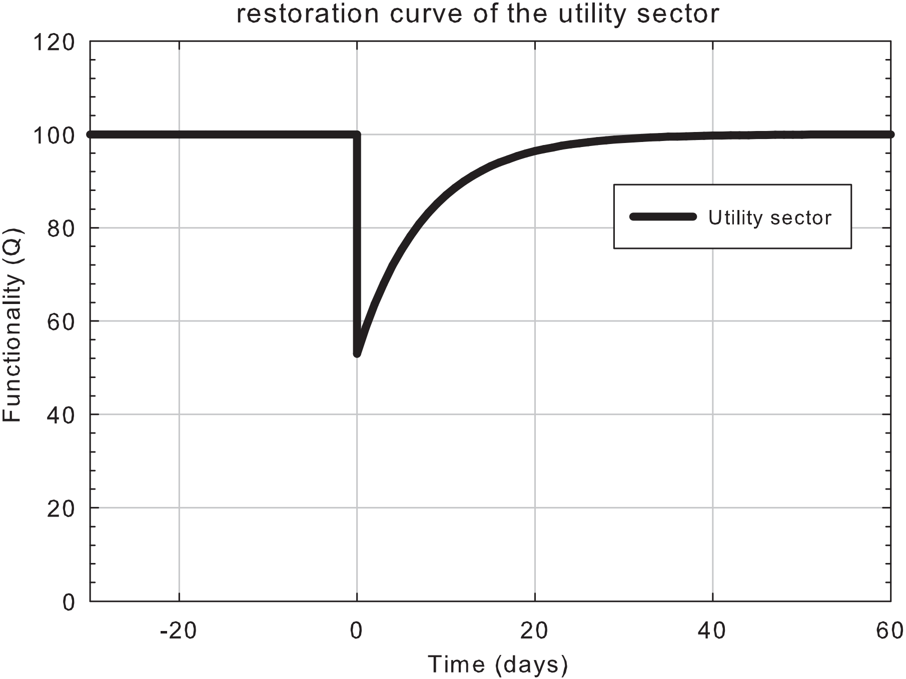
Region of interest


Industries' inoperability
Inoperability [%]
1
0.1
0.01
0.001
0.0001
Utilities disfunctionality
Transportation and wharehouse disfunctionality
Mining sector disfunctionality
Mining
Transportation and warehousing
Construction
Professional and business services
Manufacturing
Wholesale trade
Finance, insurance, real estate, rental and leasing
arts, entaitainement, recreation, accomodation and food services
information
other services, except Government
Government
Retail trade
Agriculture, foresty, fishing and hunting
Educational services, health care and social assistance
utilities


10% disfunctionality of utility sector
Inoperability [%]
100
10
1
0.1
0.01
Unscaled values
Scaled values (Eq. 17)
Utilities
Liquid Fuel
Transportation
Buildings
solid waste, water and wastwater
Critical manufacturing
Commercial Facilities
Finantial services
Communications
Emergency services
Goverment facilities
Food and agriculture
Health care and public health


restoration curve of the utility sector
Functionality (Q)
120
100
80
60
40
20
0
-20
0
20
40
60
Time (days)
Utility sector