16th World Conference on Earthquake, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 2701
Registration Code: S-R1463181584

MODELING INTERDEPENDENCIES OF CRITICAL INFRASTRUCTURES AFTER HURRICANE SANDY

P. Crupi(1), A. K. Agrawal(2), G. P. Cimellaro(3)

(1) *Student Research Assistant, Department of Structural, Building, and Geotechnical Engineering (DISEG), Politecnico di Torino, Italy, pietro.crupi@studenti.polito.it*
(2) *Professor, Department of Civil Engineering, The City College of New York, agrawal@ccny.cuny.edu*
(3) *Associate Professor, Department of Structural, Building, and Geotechnical Engineering (DISEG), Politecnico di Torino, Italy, gianpaolo.cimellaro@polito.it*

Abstract

The paper evaluates the level of inoperability and the resilience of the critical infrastructures 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, named the "inoperability ratio," is introduced to select and rank the priority actions that policymakers should implement during the restoration process. These initiatives reduce the inoperability ratio to prevent cascading effects and to improve the overall resilience in the region. Thus, these ratios also allow for primary and secondary initiatives to be distinguished.

Keywords: Resilience; Critical Infrastructure; Interdependency; Inoperability; Input-Output Model.

1. Introduction

The XXI century has already been characterized by several natural and man-made catastrophic events that occurred around the world. Lately, the increasing number of these events focused the attention on improving the community resilience so as to reduce the effects and protect people and businesses against these events. These goals can be achieved by reducing the damage induced by these events to what are known as "critical infrastructure sectors." They represent the most characteristic assets at the base of the United States economy and society, whose interconnectivity cannot be neglected when planning to increase resilience, since it allows both for their proper functioning in normal conditions and the spread of perturbation among interdependent systems when such kind of events take place.

The interconnections among the critical infrastructure sectors can be analyzed with mathematic models that allow numerical values to be given to these interdependencies, on the basis of economic data, and the way this network is affected by the disruptive event to be understood. Among others, this analysis considers the Inoperability Input-Output Model (IIM), developed by Haimes and Jiang (2001) [1] and adapted from the Leontief input-output (I-O) model for the economy (Leontief 1986) [2]. The IIM, as well as the original I-O model, are used by several researchers and analysts studying economic interdependency among industry sectors. For example, Rose et al. (1997) [3], Rose (2004) [4], and Cho et al. (2001) [5] apply the I-O model to address the electricity lifeline disruptions caused by earthquakes by estimating the regional economic impacts of this disruption. On the other hand, Haimes and Santos (2004) [6] and Santos (2006) [7] implement the IIM to analyze the impact of terrorism-induced perturbations due to interconnectedness among systems.

The IIM is firstly adopted in this paper to model the critical infrastructures network interconnectivity, so as to identify and rank the different types of dependencies. Secondly, it increases the understanding of the cascading effects that took place in the systems network of the New York metropolitan area hit by Hurricane Sandy in October 2012. The results of the model in terms of inoperability can help policymakers identify the best intervention strategy to implement to limit the impact and the consequences of future similar events. For this purpose, a new parameter, named the "inoperability ratio," is evaluated in order to better numerically describe the influence of the damages that mutually affect the sectors. Based on some assumptions, this parameter is calculated for a perturbation or functionality reduction that the disruptive external event induces on the "utilities," "liquid fuel," and "transportation" sectors. The values are realistically confirmed by several examples regarding the influence among these sectors in terms of indirect damage reported during Hurricane Sandy. This ratio is also adopted to select and rank the priority initiatives, among the many, that should be implemented to reduce the impact of future similar disruptive events on the network of critical infrastructures. Policymakers should focus on these initiatives aiming at reducing this parameter to values as close to zero as possible and also to limit the non-negligible inoperability induced in a sector due to damage occurring to another one. Furthermore, on the basis of the numeric value of this ratio, these initiatives can be distinguished and organized in primary and secondary initiatives.

This paper is organized as follows: Section 2 introduces the formulation and the supporting database for the application of the methodology in its static definition; then, in Section 3 the analysis focuses on the application of the methodology to the case study of Hurricane Sandy's impact on the New York metropolitan area, discussing about its unique characteristics and showing 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 hereby adopted to define the degree of interdependency among industry sectors of a national or regional economy. Based on the same economic data of the original Leontief (1986) [2] model, the IIM developed by Haimes and Jiang (2001) [1] evaluates the effects of disruptive events on the network of interconnected systems in terms of inoperability. Inoperability can be seen as a consequence of the impact of the external perturbation event on the network interconnectivity, being defined by the authors as the "inability of a system to perform its intended function."

The model quantifies these interactions among interconnected systems as a function of the economic data collected by the Bureau of Economic Analysis (BEA), which defines the national input-output accounts among industries in terms of their production and consumption of goods. The BEA provides 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 *j*, found along the columns, produced by each industry *i*, found along the rows, expressed in millions of dollars. It is given by Eq. (1):

$$V = \left[v_{ij} \right] \tag{1}$$

where V is the "make" matrix and v_{ij} is the monetary value 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. Each element of this "commodity-by-industry" matrix represents the monetary value of each commodity *i*, found along the rows, consumed by each industry *j*, found along the columns, expressed in millions of dollars. It is given by Eq. (2):

$$U = \left[u_{ij} \right] \tag{2}$$

where U is the "use" matrix and u_{ij} is the monetary value of each commodity i consumed by each industry j.

The combination of these matrices allows to calculate the Leontief technical coefficient matrix A, which numerically defines the degree of interdependency among economic industries. Firstly, each element of the above-mentioned "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 Eq. (3). For the latter, it is the total industry input x_i and together with the others defines the total industry input vector (x^T) defined in Eq. (4).

$$y^T = \left[y_1 = \sum_i v_{i1} \quad \cdots \quad y_j = \sum_i v_{ij} \quad \cdots \quad y_m = \sum_i v_{im} \right] \tag{3}$$

$$x^T = \left[x_1 = \sum_i u_{i1} \quad \cdots \quad x_j = \sum_i u_{ij} \quad \cdots \quad x_n = \sum_i u_{in} \right] \tag{4}$$

The matrices thus obtained are the normalized "make" and "use" matrices in Eq. (5) and Eq. (6):

$$\hat{V} = \frac{V}{y^T} \Leftrightarrow \left\{ \hat{v}_{ij} = \frac{v_{ij}}{y_j} \right\} \tag{5}$$

$$\hat{U} = \frac{U}{x^T} \Leftrightarrow \left\{ \hat{u}_{ij} = \frac{u_{ij}}{x_j} \right\} \tag{6}$$

where $\hat{\hat{V}}$ is the normalized "make" matrix, $\hat{v}_{ij}$ is the normalized monetary value of each commodity j produced by each industry i, y_j is the total commodity input, $\hat{U}$ is the normalized "use" matrix, and $\hat{u}_{ij}$ is the normalized monetary value of each commodity i consumed by each industry j.

These matrices are multiplied to define the "industry-by-industry" interdependency matrix A in Eq. (7):

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

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 can be specialized in order to provide a more accurate analysis of these interdependencies for a specific region of interest through what are known as RIMS II accounts. Provided by the BEA's Regional Economic Analysis Division, they are a database of regional multipliers calculated on the basis of regional personal income and wage-and-salary data that "can be used as surrogates for time-consuming and expensive surveys without compromising accuracy" (Haimes et al. 2005b) [8]. The regional multipliers are obtained from the location quotients for regional decomposition calculated through Eq. (8):

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

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 Eq. (9):

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

where A^R is the regional technical coefficient interdependency matrix, l is the location quotients vector, $\sum$ 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 (2001) [1], 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 quantifies inoperability as a reduction of production caused by perturbations to the demand, evaluating how the inoperability of a perturbed system influences the other interdependent systems through Eq. (10):

$$q = A^{*}q + c^{*} \tag{10}$$

$$c_i^{*} = \left(\hat{c}_i - \tilde{c}_i\right) / \hat{x}_i \tag{11}$$

$$a_{ij}^{*} = a_{ij}\left(\hat{x}_j / \hat{x}_i\right) \tag{12}$$

$$q_i = \left(\hat{x}_i - \tilde{x}_i\right) / \hat{x}_i \tag{13}$$

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 (Eq. (11)), 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 (Eq. (12)), 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 (Eq. (13)).

For the purpose of the present analysis, Eq. (14) is obtained for the demand-reduction regional IIM. Each element assumes the same meaning previously described but refers to a regional scale.

$$q^{R} = A^{*R}q^{R} + c^{*R} \tag{14}$$

The corresponding demand-reduction regional matrix A^{*R} can be written as in Eq. (15):

$$A^{*R} = [(diag(\hat{x}^{R}))^{-1} A^{R} (diag(\hat{x}^{R}))] \Leftrightarrow \left\{a_{ij}^{*R} = a_{ij}^{R}\left(\hat{x}_j^{R} / \hat{x}_i^{R}\right)\right\} \tag{15}$$

The values of inoperability provided by Eq. (14) for the sectors interconnected with the perturbed sector are extremely low when compared to the inoperability of the sector subjected to functionality reduction, which is 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. In order to accomplish for that, these values can be used as magnitudes to scale the inoperability of the other sectors proportionally to that of the perturbed sector. The new percentages of inoperability are given by Eq. (16):

$$q^{R}_{j\ scaled} = q_p^{R}\left(q_j^{R} / \sum q_j^{R}\right) \tag{16}$$

where $q^{R}_{j\,scaled}$ is the new value of induced inoperability, calculated with the regional model for the j^{th} sectors not directly subjected to functionality reduction, q^{R}_{j} is the corresponding 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, " that defines the inoperability induced in a sector as a function of the inoperability of the perturbed sector. It is given by Eq. (17):

$$Q_{pj} = q^{R}_{j\ scaled} / q_p^{R} \tag{17}$$

where Q_{pj} is the inoperability ratio, $q^{R}_{j\ scaled}$ 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 to evaluate both the inoperability induced and the degree of interconnections.

3. Case Study: Hurricane Sandy's Impact on the New York Metropolitan Area

3.1 Overview

Hurricane Sandy was the last hurricane of the 2012 Atlantic season that impacted 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 usually referred to it as "Superstorm" due to its unique features and strength. It was characterized by an unusual and distinctive westbound track, caused by its interaction with two other weather systems that were taking place in the Atlantic Ocean around that time that intensified the storm winds and increased its extent up to 1800 km in diameter. It also 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. Storm surge 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 (Blake et al. 2013) [9]. Overall, more than 1000 km of U.S. coastline were impacted mostly by the storm surge generated by Hurricane Sandy.

One of the most affected regions along Sandy's path was the metropolitan area of New York. 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 (Kunz et al. 2013) [10], corresponding to a 1% probability of being hit by similar catastrophic events during the season, as assessed by Colorado State University (typhoon.atmos.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. The hurricane also impacted an area that is characterized by a very developed network of critical infrastructure 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 damage that occurred to the infrastructures of this selected area are outlined in detail by the New York City Government (2013) [11] report "*PlaNYC: A Stronger, More Resilient New York*," as well as other supporting damage data provided by Blake et al. (2013) [9], Kunz et al. (2013) [10], and Botts et al. (2013) [12] researches, among others. Moreover, for the purposes of their study, Haraguchi and Kim (2014) [13] summarize the detailed damage analysis provided by the New York City Government. 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," and mostly occurred to sector facilities. Indirect damages are those "caused by functional problems such as power outage, overload, and impacts of failures in other sectors," therefore can be attributed to the effects that these physical damages induce on the other sectors. Their damage analysis confirms the high degree of interdependency existing among the critical infrastructure sectors: each sector strongly relies on the services and the outputs provided by other connected infrastructures. As highlighted by Haraguchi and Kim (2014) [13], 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 (Rose et al. 1997) [3].

As a consequence of this interconnectedness, several cascading effects on the networked sectors of the area have been reported. For example, Flegenheimer (2012) [14] reported that 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 (2013) [11], 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. These are just some of the several cascading effects that 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 slowed down 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 (2014) [13], 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 so as to increase its ability to withstand and recover from similar future events. 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 (2013) [11] report. 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 Haraguchi and Kim (2014) [13], 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 others 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.

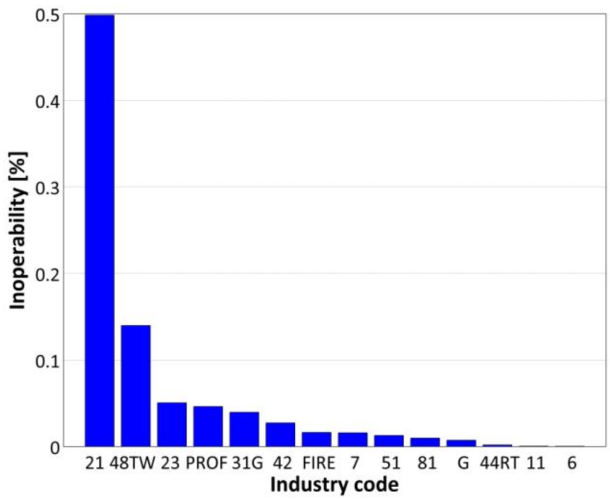
3.2 Application of the Methodology to the Case Study

The regional demand-reduction IIM is applied to evaluate the degree of interdependency among economic industries or critical infrastructure sectors in the identified portion of the metropolitan area of New York. 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, consisting of counties covering the five boroughs of the city of New York and the counties of the state of New Jersey that fall into its metropolitan area. 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. 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. Their level of aggregation does not correspond with the same of the make and use matrices, thus, on the basis of some assumptions, the original multipliers are manipulated to obtain the adapted multipliers reported in Table 1.

Three regional demand-side interdependency matrices A^{*R} are calculated according to Eq. (15) 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 ratio between the U.S. GDP (14,530,716 million dollars) and the combined GDP relative to New York City and New Jersey (1,446,659 million dollars) in 2012 which is equal to about 1/10.

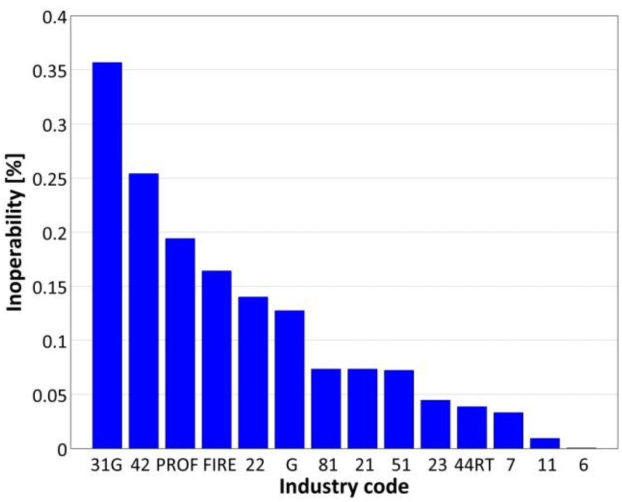
Table 1 – Adapted multipliers for regional decomposition

Code	Industries	$li_{utilities}$	li_{transp}	li_{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	0.00085	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



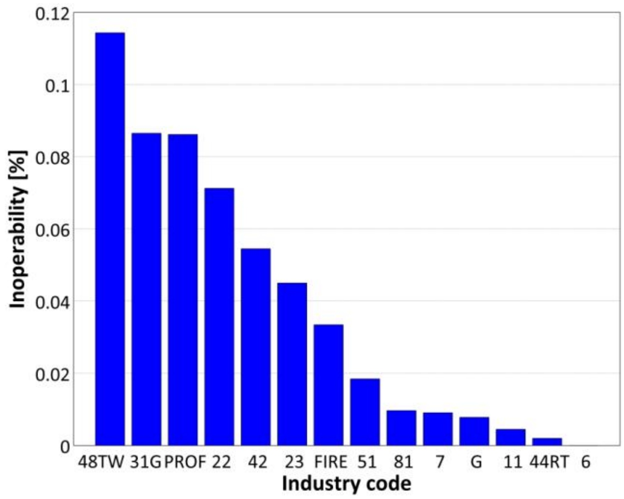
Code	Industries	q^R [%]
21	Mining	0.50
48TW	Transportation and warehousing	0.14
23	Construction	0.05
PROF	Professional and business services	0.05
31G	Manufacturing	0.04
42	Wholesale trade	0.03
FIRE	Finance, insurance, real estate, rental, and leasing	0.02
7	Arts, entertainment, recreation, accommodation, and food services	0.02
51	Information	0.01
81	Other services, except government	0.01
G	Government	0.01
44RT	Retail trade	0.00
11	Agriculture, forestry, fishing, and hunting	0.00
6	Educational services, health care, and social assistance	0.00

Fig. 1 – Industries' inoperability ranking due to functionality reduction in utilities sector



Code	Industries	q^R [%]
31G	Manufacturing	0.36
42	Wholesale trade	0.25
PROF	Professional and business services	0.19
FIRE	Finance, insurance, real estate, rental, and leasing	0.16
22	Utilities	0.14
G	Government	0.13
81	Other services, except government	0.07
21	Mining	0.07
51	Information	0.07
23	Construction	0.04
44RT	Retail trade	0.04
7	Arts, entertainment, recreation, accommodation, and food services	0.03
11	Agriculture, forestry, fishing, and hunting	0.01
6	Educational services, health care, and social assistance	0.00

Fig. 2 – Industries' inoperability ranking due to functionality reduction in transportation and warehousing sector



Code	Industries	q^R [%]
48TW	Transportation and warehousing	0.11
31G	Manufacturing	0.09
PROF	Professional and business services	0.09
22	Utilities	0.07
42	Wholesale trade	0.05
23	Construction	0.04
FIRE	Finance, insurance, real estate, rental, and leasing	0.03
51	Information	0.02
81	Other services, except government	0.01
7	Arts, entertainment, recreation, accommodation, and food services	0.01
G	Government	0.01
11	Agriculture, forestry, fishing, and hunting	0.00
44RT	Retail trade	0.00
6	Educational services, health care, and social assistance	0.00

Fig. 3 – Industries' inoperability ranking due to functionality reduction in mining sector

The model is then 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. Fig. 1, Fig. 2, and Fig. 3 report 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. The inoperability rankings and graphs do not show the inoperability of the sectors subjected to reduction of functionality since they are an order of magnitude higher than the others. The specific sector inoperability does not have an unique value but it changes in value and in position in the rankings according to the sector subjected to functionality reduction. 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 mean that this sector does not strongly depend on the others and it has a high ability to isolate itself that appears especially during emergency situations.

Table 2 – Correspondence between BEA industries and critical infrastructure sectors

Code	Industries	Critical infrastructure sectors
11	Agriculture, forestry, fishing, and hunting	*Food and Agricolture*
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 services	*Commercial Facilities*
81	Other services, except government	*Emergencies Services*
G	Government	*Government Facilities*

A correspondence among the industries of the economic data and the critical infrastructure sectors is needed and it is assumed to apply the model to the network of sectors impacted by Sandy. Table 2 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 (2013) [11] report (in bold). 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. Also, the original definition given by the Department of Homeland Security (DHS) (in italic) 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 above-mentioned report. For the purpose of this analysis, these correspondences are however assumed and provide satisfying results.

Table 3 – New percentages of inoperability due to functionality reduction in utilities sector

% INOPERABILITY FOR SECTORS												
Utilities	Liquid Fuels	Transportation	Buildings	Solid Waste, Water and Wastewater	Critical Manufacturing	Commercial Facilities	Financial Services	Communications	Emergencies Services	Government Facilities	Food and Agricolture	Healthcare and Public Health
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

Table 4 – New percentages of inoperability due to functionality reduction in liquid fuel sector

% INOPERABILITY FOR SECTORS												
Liquid Fuels	Transportation	Critical Manufacturing	Solid Waste, Water and Wastewater	Utilities	Commercial Facilities	Buildings	Financial Services	Communications	Emergencies Services	Government Facilities	Food and Agricolture	Healthcare and Public Health
10.00	2.15	1.63	1.62	1.34	1.03	0.85	0.63	0.35	0.18	0.15	0.08	0.00
20.00	4.30	3.25	3.24	2.68	2.05	1.69	1.26	0.69	0.36	0.29	0.17	0.00
30.00	6.45	4.88	4.86	4.02	3.08	2.54	1.89	1.04	0.54	0.44	0.25	0.00

Table 5 – 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 Agricolture	Healthcare and Public Health
10.00	2.36	1.68	1.29	1.09	0.93	0.84	0.49	0.49	0.48	0.30	0.06	0.00
20.00	4.73	3.36	2.57	2.17	1.85	1.69	0.97	0.97	0.96	0.59	0.12	0.01
30.00	7.09	5.05	3.86	3.26	2.78	2.53	1.46	1.46	1.44	0.89	0.19	0.01

Table 3, Table 4, and Table 5 report the new inoperability calculated using Eq. (16). These inoperabilities correspond to increasing percentages of perturbation to the three sectors under analysis, which now, after the supposed correspondence in Table 2, are "utilities," "liquid fuel," and "transportation".

Table 6 shows the inoperability ratios calculated using Eq. (17) for functionality reductions occurring singularly to each of the three sectors on which this paper focuses, which, after the correspondence in Table 2, are "utilities," "transportation," and "liquid fuel." 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.

Table 6 – Inoperability ratios for functionality reductions of utilities, transportation, and liquid fuel sectors

	Utilities	Transportation	Liquid Fuel
UTILITIES	α%	0.16α%	0.59α%
TRANSPORTATION	0.09β%	β%	0.05β%
LIQUID FUEL	0.13γ%	0.22γ%	γ%

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. 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 0.59α. On the other hand, the inoperability of the utilities sector induced by a functionality reduction to the liquid fuel sector is always 13% (0.13γ) 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 (0.16α) and vice versa (0.09β), as well as the impact of the transportation disruption on liquid fuel sector (0.05β), and vice versa (0.22γ). Overall, it is possible to explain these percentages and their lack of reciprocity by taking into account 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 have to 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 6 can also be used to analyze disruptions in two sectors, for example, the combined effect of disruptions on utilities and fuel supply on transportation as 0.16α+0.22γ. 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 6 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 because, as reported by the damage analysis, indirect damage is not negligible, and also 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. Table 7 through Table 12 reported in Appendix I give a better view of this selection of initiatives. 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, such as when a high percentage of inoperability ratio is obtained; 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.

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 make a selection of the most priority initiatives to adopt in the aftermath of a disruptive event.

4. Conclusions

The aim of this study is to analyze the impact of Hurricane Sandy on the network of 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 on the basis of numerical data regarding their economic interdependency. The evaluation of the sectors' inoperability confirms the damage analysis and the importance of utilities, liquid fuel, and transportation sectors in the network, as these were the most damaged sectors that caused cascading effects because of network interdependency.

In addition, the model is used to identify the priority actions to adopt during the various stages of emergency management. It means that it can be seen as a support tool that better guides policymakers in the selection of the best actions that, among the many possible, should be considered for the determination of an optimal intervention strategy. The output of the model in terms of inoperability is used to define a new parameter that supports this prioritization. This parameter, called "inoperability ratio," is defined as the percentage of inoperability that the perturbation in a sector causes on another. It is calculated for perturbations affecting utilities, liquid fuel, and transportation sectors. When the impacted sector is not perturbed sector, the highest (0.59α) and the lowest (0.05β) inoperability ratios are both reported for the liquid fuel sector for perturbations that occurred to the utilities and transportation sectors, respectively.

In conclusion, the priority initiatives that reduce the inoperability ratio between different sectors should be adopted before the others in order to limit the inoperability induced by damage not directly affecting that sector. The damage analysis shows that the indirect damage account for a significant component of the overall amount of damage experienced by a sector. Hence, attention should firstly be focused on the initiatives that limit them. Based on the value of the inoperability ratios, these initiatives are further distinguished between primary and secondary initiatives, where the former are those that would reduce the higher inoperability ratio and secondary initiatives would instead limit the lower inoperability ratio. The other actions are not negligible and should also be taken into account, even though they would benefit only the sector for which they are proposed.

A possible development of this analysis could focus on the identification of other parameters that would help evaluating the contribution given by each initiative in the reduction of the percentage of inoperability. Further modifications to the model should be introduced to account for this, since the original model does not define the intraconnections, which are the dependencies among the infrastructures of the same sector. Also, additional data would be required, for example, to define the importance that each asset has in the functioning of the overall sector.

5. Acknowledgement

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC IDEal reSCUE 637842 of the project IDEAL RESCUE - Integrated DEsign and control of Sustainable CommUnities during Emergencies.

6. References

[1] Haimes, Y. Y., Jiang, P. (2001): Leontief-based model of risk in complex interconnected infrastructures. *Journal of Infrastructure systems*, **7**(1), 1–12.

[2] Leontief, W.W. (1986): Input-output economics. Oxford University Press on Demand.

[3] Rose, A., Benavides, J., Chang, S. E., Szczesniak, P., Lim, D. (1997): The regional economic impact of an earthquake: Direct and indirect effects of electricity lifeline disruptions. *Journal of Regional Science*, **37**(3), 437–458.

[4] Rose, A. (2004): Economic principles, issues, and research priorities in hazard loss estimation. Springer, 13–36.

[5] Cho, S., Gordon, P., Moore, I., James, E., Richardson, H. W., Shinozuka, M., Chang, S. (2001): Integrating Transportation Network and Regional Economic Models to Estimate The Costs of a Large Urban Earthquake. *Journal of Regional Science*, **41**(1), 39–65.

[6] Santos, J. R., Haimes, Y. Y. (2004): Modeling the Demand Reduction Input-Output (IO) Inoperability Due to Terrorism of Interconnected Infrastructures. *Risk Analysis*, **24**(6), 1437–1451.

[7] Santos, J. R. (2006): Inoperability input-output modeling of disruptions to interdependent economic systems. *Systems Engineering*, **9**(1), 20–34.

[8] Haimes, Y. Y., Horowitz, B. M., Lambert, J. H., Santos, J. R., Lian, C., Crowther, K. G. (2005b): Inoperability input-output model for interdependent infrastructure sectors. I: Theory and methodology. *Journal of Infrastructure Systems*, **11**(2), 67–79.

[9] Blake, E. S., Kimberlain, T. B., Berg, R. J., Cangialosi, J., Beven II, J. L. (2013): Tropical Cyclone Report: Hurricane Sandy. National Hurricane Center, 12, 1–10.

[10] Kunz, M., Mhr, B., Kunz-Plapp, T., Daniell, J., Khazai, B., Wenzel, F., Vannieuwenhuyse, M., Comes, T., Elmer, F., Schrter, K. (2013): Investigation of Superstorm Sandy 2012 in a multi-disciplinary approach. *Natural Hazards and Earth System Sciences*, **13**(10), 2579.

[11] New York City Government (2013): PlaNYC: A Stronger, More Resilient New York.

[12] Botts, H., Du, W., Jeffery, T., Kolk, S., Pennycook, A. Z., Suhr, L. (2013): Core-Logic Storm Surge Report.

[13] Haraguchi, M., Kim, S. (2014): Critical infrastructure systems: A case study of the interconnectedness of risks posed by Hurricane Sandy for New York City.

[14] Flegenheimer, M. (2012): New York subway repairs border on the edge of magic (available at: http://www.nytimes.com/2012/11/01/nyregion/new-yorkers-cling-to-hope-of-a-better-677commute.html). The New York Times.

7. Appendix I: Tables of Primary and Secondary Initiatives

Table 7 – Initiatives for the liquid fuel sector for functionality reduction of utilities sector

PRIMARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF UTILITIES		
UTILITIES α%	**LIQUID FUEL 0.59α%**	
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 8 – Initiatives for the utilities sector for functionality reduction of liquid fuel sector

SECONDARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF LIQUID FUEL		
LIQUID FUEL γ%	**UTILITIES 0.13γ%**	
Causes	**Effects**	**Initiatives**
Fuel shortage	Limited use of in-place backup electric generators as alternative power sources	15: Speed up service restoration via pre-connections for mobile substations
Fuel shortage	Inadequate fuel supply for power and steam generation plants that preemptively switched to fuel and consequent limited use of fuel for heating	9: Strengthening of New York City's power supply
Fuel shortage	Delays in refueling utility crews and delays in their restoration efforts	22: Incorporation of resiliency into the design of City electric vehicle initiatives and pilot storage technologies
Diversion of diesel fuel of the heating oil reserve for fueling vehicles	Reduction of availability of fuel for building heating and use of other heating sources	21: Scale up of distributed generation (DG) and micro-grids (photovoltaic)

Table 9 – Initiatives for the transportation sector for functionality reduction of utilities sector

SECONDARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF UTILITIES		
UTILITIES **α%**	**TRANSPORTATION** **0.16α%**	
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

Table 10 – Initiatives for the utilities sector for functionality reduction of transportation sector

PRIMARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF TRANSPORTATION		
TRANSPORTATION **β%**	**UTILITIES** **0.09β%**	
Causes	**Effects**	**Initiatives**
Street damage and closure	Delayed utility restoration efforts and collection of damage information	13: Implementation of smart grid technologies
Street damage	Limited access for repair crews to critical customers affected by utility damages	14: Speed up service restoration for critical customers via system configuration 23: Improvement of backup generation for critical customers

Table 11 – Initiatives for the liquid fuel sector for functionality reduction of transportation sector

SECONDARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF TRANSPORTATION		
TRANSPORTATION β%	**LIQUID FUEL 0.05β%**	
Causes	**Effects**	**Initiatives**
Street damage	Limited access to fuel facilities	8: Development of a package of City, State, and Federal regulatory actions to address liquid fuel shortages during emergencies
Street damage	Delays in fuel supply and fuel delivery trucks detours	9: Hardening of municipal fueling stations and enhancing of mobile fueling capability

Table 12 – Initiatives for the transportation sector for functionality reduction of liquid fuel sector

PRIMARY INITIATIVES FOR FUNCTIONALITY REDUCTION OF LIQUID FUEL		
LIQUID FUEL γ%	**TRANSPORTATION 0.22γ%**	
Causes	**Effects**	**Initiatives**
Closure of gas stations or limitation of their operations	Additional traffic congestions in proximity of open fuel retailers	7: Modification of price gouging laws and increase of flexibility of gas station supply contracts
Fuel disruption	Difficulties of refueling and limitation of emergency and critical storm response vehicle operations	9: Hardening of municipal fueling stations and enhancing of mobile fueling capability
Waivers for fuel transportation	More dangerous fuel trucks on the streets	15: Improvement of communications about the restoration of transportation services
Gasoline rationing	Reduced possibility to use private vehicles and overwhelming of other systems	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