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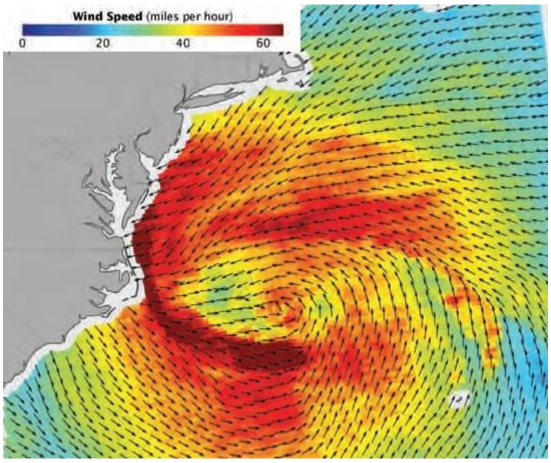
Introduction

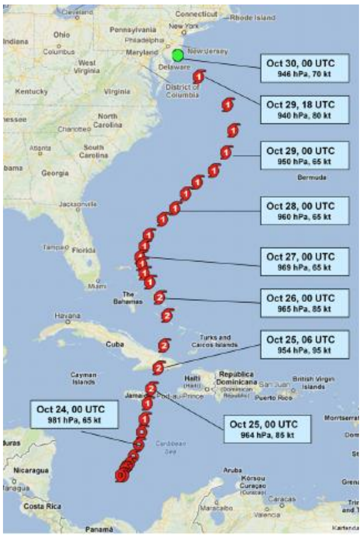
The beginning of the new century has been characterized by an increased number of catastrophic events taking place around the world. These events refers to multiple man-made and natural events that hit communities with different social, economic, and political characteristics while always causing human casualties and damage to private and public possessions that are often uncountable. Lately, attention has been focused on reducing the effects and protecting people and businesses against these extreme events by improving their resilience at the community level. This is described as an increase in their ability to withstand the impact and the consequences of similar, as well as more powerful, extreme and disruptive events and to recover from them in the shortest amount of time possible. In particular, this goal can be achieved by limiting the damage that during these events are reported by the so called "critical infrastructure sectors," which represent the "backbone" for the functioning of the United States. The networking among these sectors represents their strong points, which allows for their proper functioning in normal condition, as well as one of their weakest points, since it allows a perturbation to a sector to easily propagate to other interconnected sectors. These interconnections among the critical infrastructure sectors can be analyzed with a mathematic model that, based on economic data, can be applied to give numerical values to these interdependencies and to model the interaction between this network and the disruptive event. Among the several models applicable, this analysis adopts the Inoperability Input-Output Model developed by Haimes and Jang (2001) to model the network interconnectivity, understand the propagation of cascading effects, and help policy-makers to identify the best intervention strategy to implement in response to the event.

Hurricane Sandy and The Impact on The Critical Infrastructure Systems of The Metropolitan Area of New York

Hurricane Sandy was one of the most remarkable natural catastrophic events that took place in over the past few years. It was the last hurricane of the 2012 Atlantic season impacting the Atlantic coast of North America, causing human casualties and billion 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 used to 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. Fig. 1 gives an idea of the size and the speed of Sandy's winds while it was moving along the U.S. Atlantic coast. 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 full moon, enhancing the effect of storm surge waters that the high-speed winds were pushing towards the coast. As a consequence, 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 at Battery Park on the southern tip of Manhattan were a storm surge of 9.56 ft above normal tide levels was reported (Blake et al., 2013). Overall, more than 1000 kilometers of U. S. coastline were impacted mostly by the storm surge generated by Hurricane Sandy. Fig. 2 evidences the unusual track of the storm, as well as some of its features, such as storm category, wind speed, and minimum sea level pressure.

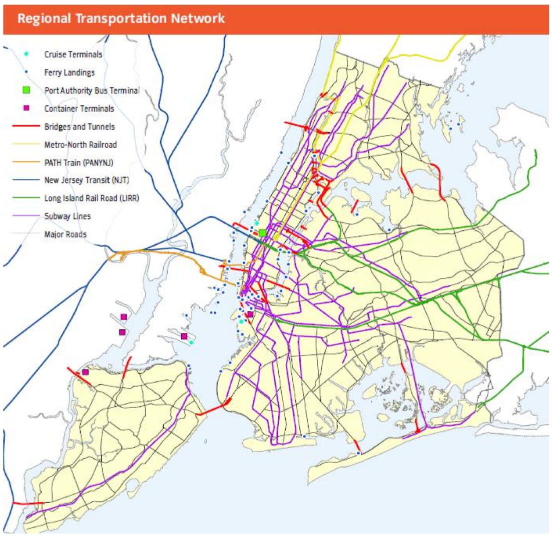
[Fig. 1-2 near here]





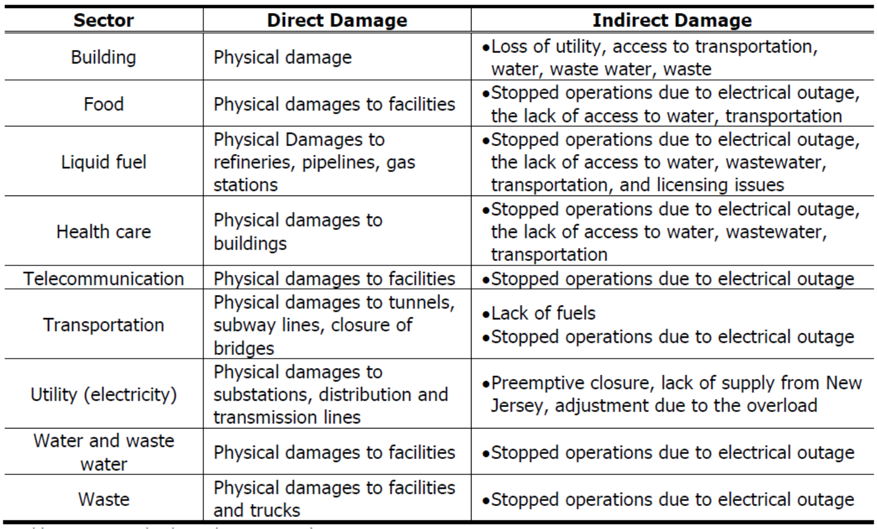
One of the most affected regions along Sandy’s path was the metropolitan area of New York. Several reasons brought this analysis to focus on the events occurred in New York City and New Jersey counties falling into the metropolitan area. On one hand, this area is not commonly associated with hurricane 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), corresponding to a 1% probability of being hit by similar catastrophic events during the season, as assessed by the Colorado State University (http://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 because of the hurricane itself and its effects, such as flooding, the storm surge, and high-speed winds. One more reason is that the hurricane 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. In particular, Fig. 3 gives a better idea of the intricacy of the solely transportation system in New York City and its surrounding area.

[Fig. 3 near here]



A detailed analysis of the damage occurred to the infrastructures of this selected area has been outlined by the New York City Government (2013) report "*PlaNYC: A Stronger, More Resilient New York*," as well as other supporting damage data has been provided by the researches published by Kunz et al. (2012), Blake et al. (2013), and Botts et al. (2013), among others. Moreover, for the purposes of their research, Haraguchi et al. (2014) summarized the detailed damage analysis provided by the New York City Government in Table 1. They distinguished the damage occurred to the critical infrastructure sectors between 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 showed by Table 1, direct damages are mostly physical damages to sector facilities while the indirect damages can be attributed to the effects that these physical damages induce on the other sectors.

[Table 1 near here]



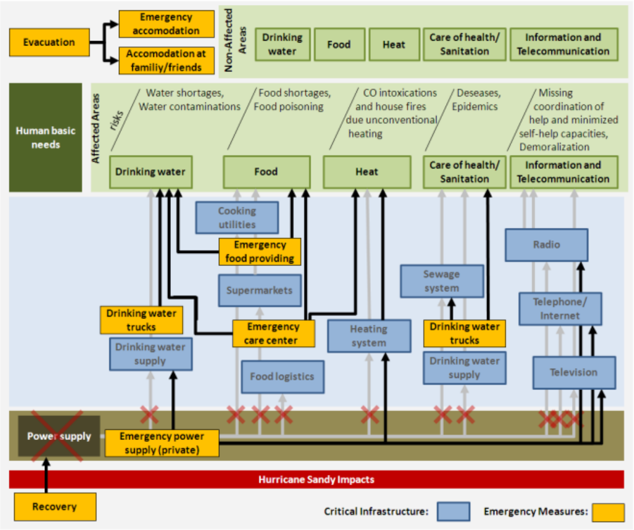
Sector	Direct Damage	Indirect Damage
Building	Physical damage	•Loss of utility, access to transportation, water, waste water, waste
Food	Physical damages to facilities	•Stopped operations due to electrical outage, the lack of access to water, transportation
Liquid fuel	Physical Damages to refineries, pipelines, gas stations	•Stopped operations due to electrical outage, the lack of access to water, wastewater, transportation, and licensing issues
Health care	Physical damages to buildings	•Stopped operations due to electrical outage, the lack of access to water, wastewater, transportation
Telecommunication	Physical damages to facilities	•Stopped operations due to electrical outage
Transportation	Physical damages to tunnels, subway lines, closure of bridges	•Lack of fuels •Stopped operations due to electrical outage
Utility (electricity)	Physical damages to substations, distribution 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

Moreover, the damage analysis confirms the high degree of interdependency existing among the critical infrastructure sectors, meaning that each one of them strongly rely on the services and the outputs provided by other connected systems. As highlighted by Haraguchi et al.

(2014), 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).

As a consequence of this interconnectedness, several cascading effects on the networked sectors of the area have been reported. For example, as reported by Flegenheimer (2012), power outages limited efforts for the restoration of subway service, since the running of 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), power outages contributed to the global transportation network shutdown, as well as to the inoperability of liquid fuel facilities. Moreover, the deployment of utility restoration crews and emergencies vehicles to areas in need was delayed by damage that occurred to the transportation infrastructures and by the fuel disruption. In addition, buildings, hospitals and other healthcare centers had to be evacuated due to the power outages and the lack of fuel and failure of emergency backup generators. These cascading effects led to further indirect damages and problems to the entire network. For example, long lines and consequent traffic congestions 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 hampered utility efforts to reach and repair the damage to impacted facilities that provide power to streets as well as buildings, thus the damage to transportation infrastructures affected both the utilities and buildings sectors. Overall, as also confirmed by Haraguchi et al. (2014) 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. Fig. 4 gives a better idea of the cascading effects generated only by power outages during Hurricane Sandy.

[Fig. 4 near here]



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 several infrastructures. It launched the so called Special Initiative for Rebuilding and Resiliency (SIRR) that produced a plan of strategies to adopt in order to strengthen the protection of New York's infrastructures, buildings, and communities from the impacts of future climate risks, published in the New York City Government (2013) report *PlaNYC: A Stronger, More Resilient New York*. Among the more of 200 initiatives outlined, our attention was focused on analyzing those concerning utilities, liquid fuel, and transportation sectors. Basing on the damage analysis, these were the most directly damaged sectors by the storm and, as confirmed by Table 1, those that caused the majority of indirect damages. They can also be considered as the key sectors in the overall infrastructure network, because of the strong dependency of the others sectors on them and also the high concentration of their facilities in the area under analysis, from refineries to power plants and a dense transportation system.

Inoperability Input-Output Model (IIM)

The Inoperability Input-Output Model (IIM) was proposed by Haimes and Jiang (2001) as an adaptation of the original input-output model, developed by Leontief (1951, 1986) to define the degree of interdependency among industry sectors of a national or regional economy. Basing on the same economic data of the Leontief's 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 the network interconnectedness.

The model quantify these interactions among the interdependent systems basing on the economic data provided by the Bureau of Economic Analysis (BEA). This supporting database defines the national input-output accounts among industries in terms of their production and consumption of goods through the so-called 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 along the columns produced by each industry along the rows expressed in millions of dollars. On the other hand, the use matrix defines the same interaction in terms of consumption of commodities. It is an "commodity-by-industry" matrix in which each element represents the monetary value of each commodity along the rows consumed by each industry along the columns expressed in millions of dollars. A combination of these matrices is used to calculate the so-called Leontief technical coefficient matrix A that numerically defines the degree of interdependency among economic industries. Firstly, the elements of the "make" and "use" matrices are divided by their respective column summations, defining the so-called normalized "make" and "use" matrices. The matrices so obtained are then multiplied each other, so as to define the "industry-by-industry" interdependency matrix A reported in Eq. 3.

$$V = \begin{bmatrix} v_{11} & \cdots & v_{1j} & \cdots & v_{1m} \\ \vdots & & \vdots & & \vdots \\ v_{i1} & \cdots & v_{ij} & \cdots & v_{im} \\ \vdots & & \vdots & & \vdots \\ v_{n1} & \cdots & v_{nj} & \cdots & v_{nm} \end{bmatrix} \Rightarrow \hat{V} = \frac{V}{y^T} \Leftrightarrow \left\{ \hat{v}_{ij} = \frac{v_{ij}}{y_j} \right\} \tag{1}$$

$$U = \begin{bmatrix} u_{11} & \cdots & u_{1j} & \cdots & u_{1n} \\ \vdots & & \vdots & & \vdots \\ u_{i1} & \cdots & u_{ij} & \cdots & u_{in} \\ \vdots & & \vdots & & \vdots \\ u_{m1} & \cdots & u_{mj} & \cdots & u_{mn} \end{bmatrix} \Rightarrow \hat{U} = \frac{U}{x^T} \Leftrightarrow \left\{ \hat{u}_{ij} = \frac{u_{ij}}{x_j} \right\} \tag{2}$$

$$A = \hat{V}\hat{U} \Leftrightarrow \left\{ a_{ij} = \sum_k \hat{v}_{ik} \hat{u}_{kj} \right\} \tag{3}$$

This interdependency matrix defines the degree of dependency of the production output of the each industry from the production input given by each of the others industries at the national U.S. economic level. In order to provide a more accurate analysis of these interdependencies for a specific region of interest, this matrix can be specialized through the so-called 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. As reported by Haimes (2005), "empirical tests suggest that regional multipliers can be used as surrogates for time-consuming and expensive surveys without compromising accuracy". Also, as reported by Miller et al. (1989), the focus of the input-output analysis to 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.

These multipliers are obtained from the so-called location quotients for regional decomposition calculated as:

$$l_i = \frac{\hat{x}_i^R / \hat{x}_s^R}{\hat{x}_i / \hat{x}_s} \tag{4}$$

where $\hat{x}_i^R$ is the regional output for the ith industry, $\hat{x}_s^R$ is the total regional output for all regional-level industries, while $\hat{x}_i$ and $\hat{x}_s$ are the corresponding national output for the ith industry and all the national-level industries.

These location quotients are used to regionalize the national technical coefficient matrix A and obtain the regional interdependency matrix AR as in Eq. 5:

$$A^R = diag[\min(l, \Sigma)]A \Leftrightarrow \left\{a_{ij}^R = \min(l_i, 1)a_{ij}\right\} \tag{5}$$

Among the several models developed by the authors, the one that can be used to analyze the impact of Hurricane Sandy in the area under analysis is the so-called demand-reduction IIM. This 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 physical one. The model evaluates how the inoperability of a perturbed system influences the other interdependent ones with various degrees of impact:

$$q = (I - A^*)^{-1} c^* \tag{6}$$

The terms of Eq. 6 are derived from the original IIM basing on the following assumptions:

- *q*: 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:

$$q = [(diag(\hat{x}))^{-1} \delta x] \Leftrightarrow q_i = \frac{\hat{x}_i - \tilde{x}_i}{\hat{x}_i} \tag{7}$$

- *A**: 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:

$$A^* = [(diag(\hat{x}))^{-1} A(diag(\hat{x}))] \Leftrightarrow a_{ij}^* = a_{ij} \left(\frac{\hat{x}_j}{\hat{x}_i} \right) \tag{8}$$

- *c**: 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:

$$c^* = [(diag(\hat{x}))^{-1} \delta c] \Leftrightarrow c_i^* = \frac{\hat{c}_i - \tilde{c}_i}{\hat{x}_i} \tag{9}$$

For the purpose of this analysis, the derived equation for the demand-reduction regional IIM is the following:

$$q^{R} = (I - A^{*R})^{-1} c^{*R} \tag{10}$$

in which each element assumes the same meaning described before but referred to a regional scale and the corresponding regional demand-side matrix A^{*R} can be written as:

$$A^{*R} = [(diag(\hat{x}^{R}))^{-1} A^{R}(diag(\hat{x}^{R}))] \Leftrightarrow \left\{ a_{ij}^{*R} = a_{ij}^{R} \left(\frac{\hat{x}_{j}^{R}}{\hat{x}_{i}^{R}} \right) \right\} \tag{11}$$

Overall, 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.

Haimes (2005) and Haimes, Lian (2006) also developed the so-called dynamic IIM, a development that “supplements and complements the static IIM.” This dynamic extension of the original IIM allows for the better evaluation and comprehension of the way industries recover from their inoperability during the following recovery phase, according to their ability to “bounce-back” to the condition they had before the event, therefore describing their resiliency. The model evaluates an exponential reduction of inoperability during the recovery phase with the following equation:

$$q_{i}(t) = e^{-k_i(1-a_{ii}^{*})t} q_{i}(0) \tag{12}$$

$q_i(0)$ is the inoperability of i sector at initial perturbation (t=0), $q_i(t)$ is the inoperability of i sector during the recovery phase ($0<t<T_i$), and $a_{ii}*$ is the diagonal element of the demand-reduction matrix A^* or A^{*R}.

k_i is the so called industry resilience coefficient or interdependency recovery rate calculated as:

$$k_{i} = \frac{\lambda}{\tau} \left(\frac{1}{1 - a_{ii}^{*}} \right) = \frac{\ln[q_{i}(0)/q_{i}(T_{i})]}{T_{i}} \left(\frac{1}{1 - a_{ii}^{*}} \right) \tag{13}$$

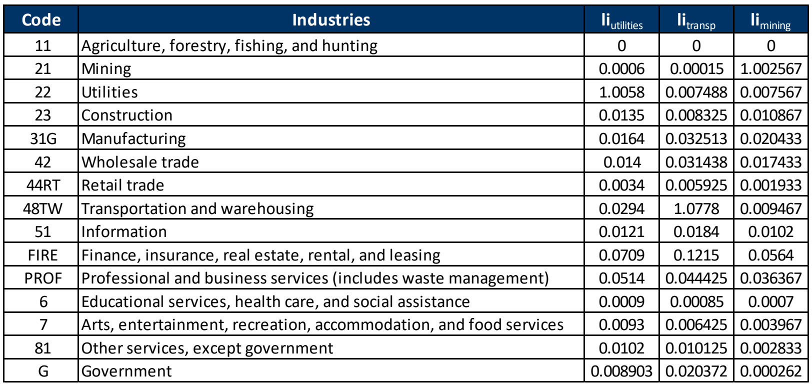
in which λ is the recovery constant, representing the ratio between the sector i inoperability, evaluated when initial perturbation occurs and when the recovery time is achieved, τ corresponds to the recovery time T_i, and $q_i(T_i)$ is the inoperability of i sector at recovery time (T_i). The ratio defines how fast/the speed in which the inoperability is recovered. The inoperability $q_i(T_i)$, as well as T_i, can be supposed 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 so much; otherwise they would contribute to reducing 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.

APPLICATION OF THE REGIONAL DEMAND-REDUCTION IIM TO (EVALUATE INTERDEPENDENCIES AMONG C.I.S. IN) HURRICANE SANDY CASE STUDY

The regional demand-reduction IIM has been 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 since Hurricane Sandy hit in October 2012. Then, the RIMS II multipliers have been purchased for the region of interest, defined as the composition of the counties corresponding with the 5 boroughs of the city of New York and the counties of the state of New Jersey that fall into its metropolitan area. Despite they refer to 2013 regional data, they can be used for the regional decomposition of 2012 national data since they do not vary much between one year and the following, 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” have been 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 have been manipulated and the adapted multipliers reported in Table X have been obtained.

[Table 2 near here]

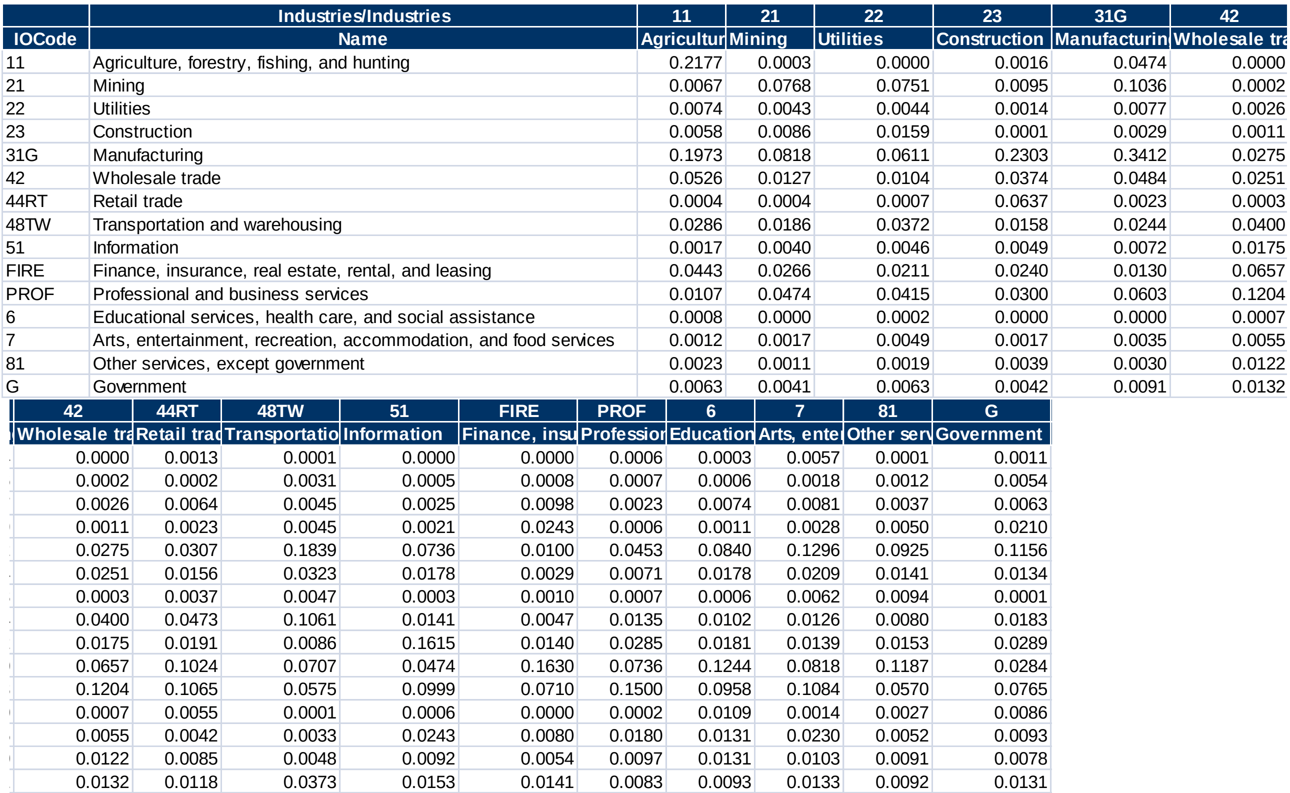


Code	Industries	$li_{utilities}$	li_{transp}	li_{mining}
11	Agriculture, forestry, fishing, and hunting	0	0	0
21	Mining	0.0006	0.00015	1.002567
22	Utilities	1.0058	0.007488	0.007567
23	Construction	0.0135	0.008325	0.010867
31G	Manufacturing	0.0164	0.032513	0.020433
42	Wholesale trade	0.014	0.031438	0.017433
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

Three type of interdependency matrices have been calculated for the application of the model. The first matrix is the national interdependency matrix A (Table 3), obtained with Eq. 3 from the combination of the normalized make and use matrices. Then, the regional interdependency matrix A^R has been calculated by considering each column of the adapted multipliers in Table 2 and implementing them in Eq. 5. A 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 which sector is subjected to demand reduction. Finally, three regional demand-side interdependency matrices A^{*R} have been calculated according to Eq. 11 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 one 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. ≈ 0.1 (1/10)

[Table 3 near here]



	Industries/Industries	11	21	22	23	31G	42	44RT	48TW	51	FIRE	PROF	6	7	81	G
IOCode	Name	Agricultur	Mining	Utilities	Construction	Manufacturin	Wholesale tra	Retail trac	Transportatio	Information	Finance, insu	Professior	Education	Arts, ente	Other serv	Government
11	Agriculture, forestry, fishing, and hunting	0.2177	0.0003	0.0000	0.0016	0.0474	0.0000	0.0013	0.0001	0.0000	0.0000	0.0006	0.0003	0.0057	0.0001	0.0011
21	Mining	0.0067	0.0768	0.0751	0.0095	0.1036	0.0002	0.0002	0.0031	0.0005	0.0008	0.0007	0.0006	0.0018	0.0012	0.0054
22	Utilities	0.0074	0.0043	0.0044	0.0014	0.0077	0.0026	0.0064	0.0045	0.0025	0.0098	0.0023	0.0074	0.0081	0.0037	0.0063
23	Construction	0.0058	0.0086	0.0159	0.0001	0.0029	0.0011	0.0023	0.0045	0.0021	0.0243	0.0006	0.0011	0.0028	0.0050	0.0210
31G	Manufacturing	0.1973	0.0818	0.0611	0.2303	0.3412	0.0275	0.0307	0.1839	0.0736	0.0100	0.0453	0.0840	0.1296	0.0925	0.1156
42	Wholesale trade	0.0526	0.0127	0.0104	0.0374	0.0484	0.0251	0.0156	0.0323	0.0178	0.0029	0.0071	0.0178	0.0209	0.0141	0.0134
44RT	Retail trade	0.0004	0.0004	0.0007	0.0637	0.0023	0.0003	0.0037	0.0047	0.0003	0.0010	0.0007	0.0006	0.0062	0.0094	0.0001
48TW	Transportation and warehousing	0.0286	0.0186	0.0372	0.0158	0.0244	0.0400	0.0473	0.1061	0.0141	0.0047	0.0135	0.0102	0.0126	0.0080	0.0183
51	Information	0.0017	0.0040	0.0046	0.0049	0.0072	0.0175	0.0191	0.0086	0.1615	0.0140	0.0285	0.0181	0.0139	0.0153	0.0289
FIRE	Finance, insurance, real estate, rental, and leasing	0.0443	0.0266	0.0211	0.0240	0.0130	0.0657	0.1024	0.0707	0.0474	0.1630	0.0736	0.1244	0.0818	0.1187	0.0284
PROF	Professional and business services	0.0107	0.0474	0.0415	0.0300	0.0603	0.1204	0.1065	0.0575	0.0999	0.0710	0.1500	0.0958	0.1084	0.0570	0.0765
6	Educational services, health care, and social assistance	0.0008	0.0000	0.0002	0.0000	0.0000	0.0007	0.0055	0.0001	0.0006	0.0000	0.0002	0.0109	0.0014	0.0027	0.0086
7	Arts, entertainment, recreation, accommodation, and food services	0.0012	0.0017	0.0049	0.0017	0.0035	0.0055	0.0042	0.0033	0.0243	0.0080	0.0180	0.0131	0.0230	0.0052	0.0093
81	Other services, except government	0.0023	0.0011	0.0019	0.0039	0.0030	0.0122	0.0085	0.0048	0.0092	0.0054	0.0097	0.0131	0.0103	0.0091	0.0078
G	Government	0.0063	0.0041	0.0063	0.0042	0.0091	0.0132	0.0118	0.0373	0.0153	0.0141	0.0083	0.0093	0.0133	0.0092	0.0131

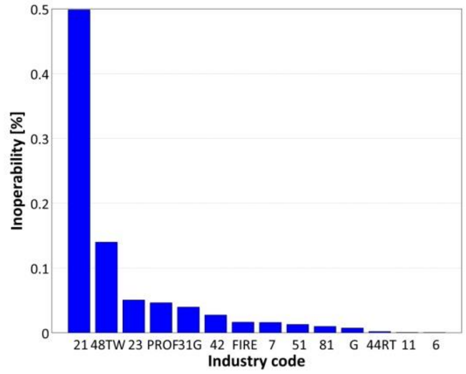
Interdependency matrix A

Finally, the model has been applied to evaluate the rankings of the most affected sectors in terms of inoperability caused by a functionality reduction to “utilities,” “mining,” and “transportation” sectors. Fig. 5, Fig. 6, and Fig. 7 and the corresponding Table 5, Table 6, and Table 7 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 to graphically represent this ranking of inoperability.

[Fig. 5 and Table 5 near here]

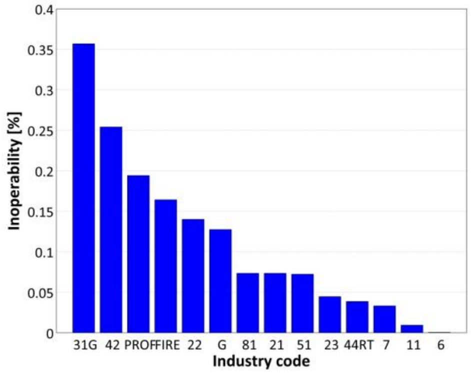
[Fig. 6 and Table 6 near here]

[Fig. 7 and Table 7 near here]



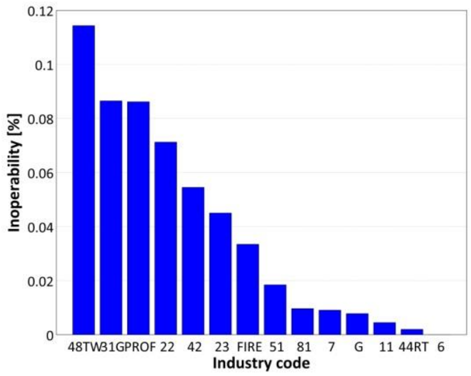
Code	Industries	q^R [%]
21	Mining	0.50
48TW	Transportation and warehousing	0.14
23	Construction	0.05
PROF	Professional and business services	0.05
31G	Manufacturing	0.04
42	Wholesale trade	0.03
FIRE	Finance, insurance, real estate, rental, and leasing	0.02
7	Arts, entertainment, recreation, accommodation, 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

Industries’ inoperability ranking due to functionality reduction to utilities industry



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

Industries’ inoperability ranking due to functionality reduction to transportation and warehousing industry



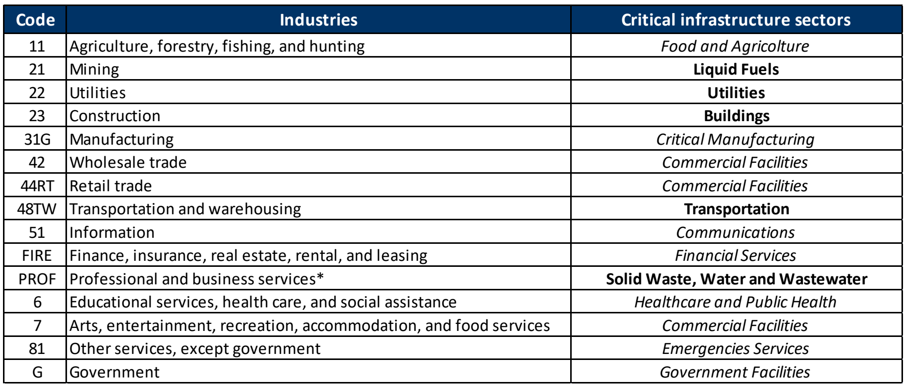
Code	Industries	q^R [%]
48TW	Transportation and warehousing	0.11
31G	Manufacturing	0.09
PROF	Professional and business services	0.09
22	Utilities	0.07
42	Wholesale trade	0.05
23	Construction	0.04
FIRE	Finance, insurance, real estate, rental, and leasing	0.03
51	Information	0.02
81	Other services, except 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

Industries’ inoperability ranking due to functionality reduction to mining industry

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, so as to allow a better visibility of the latter. 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 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 this sector does not strongly depend on the others and, as confirmed by the evidence, it has a high ability to isolate itself that appears especially during emergency situations. 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 and it has been assumed to apply the model to the network of sectors impacted by Sandy. Table 8 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 report of the government of New York City. 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 DHS has been considered when no correspondence has been 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 (2013) report. For the purpose of this analysis, these correspondences are however assumed and provide satisfying results.

[Table 8 near here]



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*

The values of inoperability provided by the method for the sectors interconnected with the perturbed one 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 values 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 follow:

$$q^{R}_{j\ scaled} = \frac{q^{R}_{j}}{\sum q^{R}_{j}} q^{R}_{p} \tag{14}$$

The original value of inoperability q^{R}_{j}, calculated with the regional model and referred to the jth sectors not directly perturbed, is divided by the sum of these induced inoperability and this ratio is then multiplied for the value of inoperability of the sector affected by functionality reduction (q^{R}_{p}). These scaled values now define a meaningful inoperability that can be compared to that of the perturbed sector and are representative of reality. Reported in Table 9, Table 10, and Table 11 are the new inoperability caused by increasing percentages of perturbation to the three sectors under analysis, which now, after the supposed correspondence in Table 8, are “utilities,” “liquid fuel,” and “transportation”.

[Table 9 near here]

[Table 10 near here]

[Table 11 near here]

		% 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
% 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	

New percentages of inoperability due to functionality reduction to 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 Agricolture	Healthcare and Public Health
% FUNCTIONALITY REDUCTION OF TRANSPORTATION SECTOR	**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	
	40.00	9.45	6.73	5.14	4.35	3.71	3.38	1.95	1.94	1.91	1.18	0.25	0.01	
	50.00	11.81	8.41	6.43	5.44	4.64	4.22	2.43	2.43	2.39	1.48	0.31	0.01	
	60.00	14.18	10.09	7.71	6.52	5.56	5.06	2.92	2.92	2.87	1.77	0.37	0.02	
	70.00	16.54	11.78	9.00	7.61	6.49	5.91	3.40	3.40	3.35	2.07	0.43	0.02	
	80.00	18.90	13.46	10.28	8.70	7.42	6.75	3.89	3.89	3.83	2.36	0.50	0.02	
	90.00	21.27	15.14	11.57	9.78	8.34	7.60	4.38	4.37	4.31	2.66	0.56	0.02	
	100.00	23.63	16.82	12.86	10.87	9.27	8.44	4.86	4.86	4.78	2.96	0.62	0.03	

New percentages of inoperability due to functionality reduction to transportation 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
% FUNCTIONALITY REDUCTION OF LIQUID FUEL SECTOR	**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
	40.00	8.60	6.51	6.48	5.36	4.10	3.39	2.52	1.39	0.73	0.59	0.34	0.00
	50.00	10.76	8.14	8.10	6.70	5.13	4.23	3.15	1.73	0.91	0.73	0.42	0.00
	60.00	12.91	9.76	9.73	8.04	6.15	5.08	3.78	2.08	1.09	0.88	0.51	0.00
	70.00	15.06	11.39	11.35	9.38	7.18	5.93	4.40	2.43	1.27	1.03	0.59	0.00
	80.00	17.21	13.02	12.97	10.72	8.20	6.77	5.03	2.77	1.45	1.17	0.67	0.00
	90.00	19.36	14.65	14.59	12.06	9.23	7.62	5.66	3.12	1.63	1.32	0.76	0.00
	100.00	21.51	16.27	16.21	13.40	10.25	8.47	6.29	3.47	1.82	1.47	0.84	0.00

New percentages of inoperability due to functionality reduction to liquid fuel sector

It is possible to notice and assume that there is a constant linear relation 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 define the inoperability induced in a sector as a function of the inoperability of the perturbed one. Eq. X 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.

$$Q_{pj} = \frac{q^{R}_{j\ scaled}}{q^{R}_{p}} \tag{15}$$

Since this ratio does not change with the increase of functionality reduction or perturbation, it can be considered as a valuable value for the evaluation of both the inoperability induced and the degree of interconnections. Table 12 reports the inoperability ratios of the three sectors this paper is focusing on. 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 12 near here]

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

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

The effect of the functionality reduction occurred to a sector on itself is always equal to the maximum, defined by α%, β%, and γ% respectively for 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 one 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 one 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%. Vice versa, the inoperability of the utilities sector induced by a functionality reduction to the liquid fuel sector is always the 13% (0.13γ%) of that of the liquid fuel sector. The same considerations can be made analyzing the impact of the utilities disruption on the transportation sector (0.16α%) and the vice versa (0.09β%), as well as the impact of the transportation disruption on liquid fuel sector (0.05β%), and the 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 the 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 terminals operations were suspended or limited also because they are not usually provided with on-site 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 that, in 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 more difficult to refuel the power restoration crews. Many other examples can be identified in order to support the other four inoperability ratio previously defined.

The percentages in Table 12 have been used to select and rank the priority initiatives among the many implementable. In particular, a policy-maker should focus on those initiatives that can reduce the inoperability ratios between different sectors to values as close to zero as possible. There is the need to focus on this selection of initiatives mainly for two reasons: as reported by the damage analysis, the indirect damage were 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 independency 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 13 to Table 18 give a better view of this selection of initiatives. They are organized 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 that 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, such as in the case of the overwhelming of transportation systems, which is a consequence of disruptions in both the utilities and liquid fuel sectors.

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

[Table 13 near here]

[Table 14 near here]

[Table 15 near here]

[Table 16 near here]

[Table 17 near here]

[Table 18 near here]

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

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	9: Planning for temporary transit services in the event of subway system suspensions 12: Planning and installation of new pedestrian and bicycle facilities

	lines, and more private vehicles traffic	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

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

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

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

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)

The results of the method can be therefore 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.

The effectiveness of these initiatives in the recovery phase following the event has been studied through the application of the dynamic IIM. In particular, it has been 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 because of Hurricane Sandy's impact on utility systems, which has been calculated with 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: U.S. Department of Energy), 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 Eq. 12. The sector recovery rate has been calculated with Eq. 13 by considering the following further assumptions:

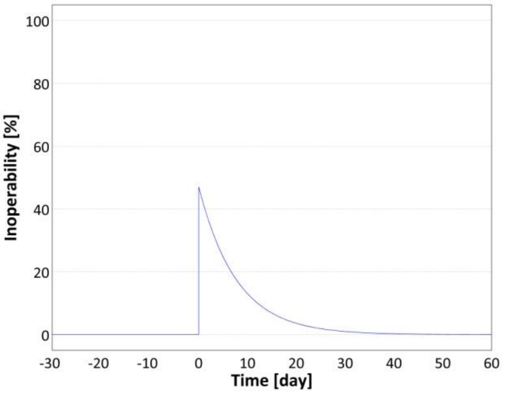
- $q_i(T_i) = 1\%$
- $T_i = 30$ days

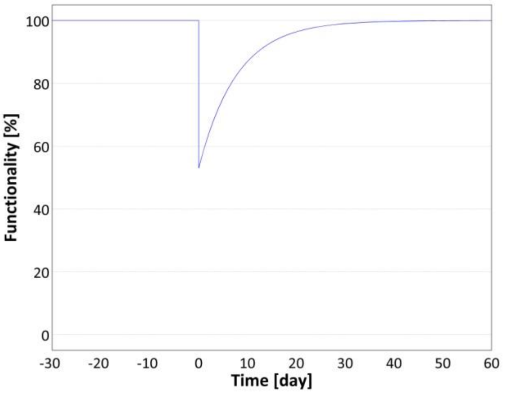
The recovery rate calculated with these values is k_i=0.1289/day. The first expression represents the residual inoperability of the utilities sector at the end of recovery time T_i. Based on these values, the utilities sector achieves a 99% recovery in 30 days. Several authors, such as Lian and Haimes (2006), have considered this 1% residual inoperability in order to apply the dynamic model for the analysis of other catastrophic events, such as a terrorist attack to the infrastructure system. According to the information and tables provided by the New York City government report, it can be considered as a reasonable value for the analysis, as well as the recovery time of 30 days.

The results of the application of the dynamic IIM are shown in Fig. 8 and Fig. 9. They both represent 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 either the inoperability or the functionality of the sector. The graphs are symmetrical since inoperability can be considered as the complement of functionality.

[Fig. 8 near here]

[Fig. 9 near here]





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

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 had not been taken into account, a plausible assumption is that the recovery time would have been longer and more serious consequences would have been experienced by the sector and therefore by the community. On the other hand, recovery time would have been shorter if some of the initiatives proposed after Sandy's impact had been already available for implementation in the event of its occurrence, improving the management of the emergency situation. This would have lead to a higher recovery rate and an increase in overall resilience.

Overall, the results obtained are representative of the reality. 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.

Conclusions

The aim of this study was 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 was used in order 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 has confirmed the damage analysis and the importance of utilities, liquid fuel, and transportation sectors in the network, as they were the most damaged sectors and those that caused the most relevant cascading effects due to other sectors' dependency on them.

In addition, the model was 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 policy-makers in the selection of the best actions that, among the many possible, should be considered for the determination of an optimal intervention strategy. In fact, just with the analysis of the initiatives and the evaluation of further criteria to organize them, it is not possible to understand which actions are the most important and why they should be implemented before others. Instead, unlike other authors' applications, the output of the model in terms of inoperability was used to define a new parameter that supports this prioritization. Such parameter, called inoperability ratio, was defined in order to understand the percentage of inoperability that the perturbation in a sector causes on another. In this study, it was calculated for perturbations affecting utilities, liquid fuel, and transportation sectors. Several examples have been found relating to the influence that one sector had on the others during Sandy in terms of indirect damage, justifying the non-negligible inoperability ratio values referring to the interaction among these sectors. When the impacted sector was not also the perturbed sector, the highest (59%) and the lowest (5%) inoperability ratios have been both reported for the liquid fuel sector for perturbations that occurred respectively to the utilities and transportation sectors.

In conclusion, the priority initiatives to adopt are those that reduce the inoperability ratio calculated between different sectors and thus limit the induced inoperability produced by damage not directly affecting that sector. The damage analysis showed that indirect damage accounts for a significant component of the overall amount of damage experienced by a sector, thus attention should firstly be focused on the initiatives that limit them. The other actions should also be considered, as they are equally important but would benefit only the sector for which they are proposed, reducing its inoperability and damage caused by the extreme event itself, and would not bring any direct improvement to the other sectors. The dynamic model realistically represents the effectiveness of these other policies during the recovery phase of the sector in the aftermath of the event. The analysis also assesses the need for an agreement among multiple decision-makers for a common planning of interventions due to the several interdependencies among the sectors that must be taken into account when working on improving the resiliency of the singular sectors.

A possible development of this analysis could focus on the identification of other parameters for the evaluation of 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 only defines the interconnections among sectors and not the intraconnections, which are the dependencies among the infrastructures of the same sector. Also, additional data would be required, for example, to define the role/importance that each asset has in the overall sector.