Community resilience index integrating network interdependencies

G. P. Cimellaro, A. M. ASCE[1], D. Solari[1], Chris S. Renschler, A. M. ASCE[2], A.M. Reinhorn, F. ASCE[3], Michel Bruneau, M. ASCE[3]

[1] Department of Structural, Building & Geotechnical Engineering (DISEG), Politecnico di Torino, room 7, Corso Duca degli Abruzzi 24, 10129 Turin, Italy PH +39 (011) 090 4801 FAX +39 (011) 090 4899, email: gianpaolo.cimellaro@polito.it
[2]Department of Geography, University at Buffalo, The State University of New York, 135 Ketter Hall, Buffalo NY, email: rensch@buffalo.edu
[3]Department of Civil, Structural & Environmental Engineering, University at Buffalo, The State University of New York, 135 Ketter Hall, Buffalo NY, email: reinhorn@buffalo.edu

ABSTRACT

Resilience index is used to analyze complex systems such as communities, when they are subjected to disasters like earthquakes, hurricanes, floods etc. in order to quantify preventive measures, emergency measures and restoration measures. Physical infrastructures within a community have a certain degree of interdependency. Interdependencies can generate cascading failures or amplification effects which can eventually affect also the restoration measures right after an extreme event. These effects can be described by a reduction of the resilience index within a given region. In this article, starting from the restoration curves of March 11th 2011 Tohoku Earthquake in Japan, a method to evaluate the interdependency index and to calculate the community resilience index is proposed. The weights of each infrastructure which are used to evaluate resilience are evaluated starting from the degree of interdependency indices which are evaluated using time series analysis.

INTRODUCTION

In the last years the scientific community increased its interested in lifelines interdependencies and resilience evaluation (Cimellaro et al., 2010[a], 2013). In literature there are several papers related to the evaluation of the interdependency index among infrastructures (Arcidiacono et al., 2012); however the taxonomy of lifeline interdependencies is given for the first time in the fundamental work by Rinaldi et al. (2001). Later Paton and Johnston (2006) have given a numerical quantification of the dependencies among different infrastructures, by using an empirical approach in which the degree of dependency among different infrastructures is function of the strength of dependency (high, medium, low dependence). Bigger et al. (2009) have collected different interdependent lifeline information associated with the 2004 hurricane season in Florida. Delamare et al. (2009) have studied the potential effect of interdependencies that may occur between the telecommunication and the electrical network and they have proposed a model that describes the behavior of these interdependent systems. More recently, Kjølle et al. (2012) have used contingency analysis (power flow), reliability analysis of power systems and cascade diagrams for investigating interdependencies, while Poljansek et al. (2012) have studied the seismic vulnerability of the European gas and electricity transmission networks from a topological point of view; network interdependency is evaluated using the strength of coupling of the interconnections, together with the seismic response.

Recently Dueñas-Osorio and Kwasinski (2012) have proposed an approach based on the post-analysis of the restoration curves. The interdependency index between infrastructures is calculated with an empirical equation that depends on the maximum positive value of the cross correlation function (*CCF*) of the two data series.

In this article it is proposed a method to evaluate resilience of a region affected by a disaster considering infrastructure interdependency. The resilience index of every infrastructure in the region is combined with others through weight coefficients, which are calculated starting from a modified version of the interdependence index proposed in the work of Dueñas-Osorio and Kwasinski (2012) where the cross correlation functions (*CCF*) are adopted. A new method to evaluate interdependency index is proposed and compared with other methods available in literature. Finally, the regional resilience index is evaluated taking in account the weights coefficients which are evaluated for every region and infrastructure considered in the analysis.

The proposed method is described using the restoration curves (Nojima, 2012) of the physical infrastructures of the 12 regions which were affected by March 11th 2011 Tohoku Earthquake.

RESTORATION CURVES OF PHYSICAL INFRASTRUCTURES AFTER 2011 TOHOKU EARTHQUAKE

In this paper the time series used for the analysis are the restoration curves recorded during March 11th 2011 Tohoku Earthquake (Nojima, 2012), in twelve Japanese regions which are listed according to the distance from the epicenter: Miyagi, Ibaraki, Fukushima, Yamagata, Akita, Ibaraki, Tochigi, Aomori, Chiba, Gunma, Saitama and Kanagawa. In Figure 1 are shown the restoration curves of three different types of lifelines (*Power delivery*, *Water supply*, *City Gas delivery*) for the regions of Miyagi, Iwate, Fukushima, Ibaraki, Aomori and Saitama. Instead for the region of Yamagata, Akita, Tochigi and Gunma are available only the data of Power delivery and Water supply, whereas for Chiba and Kanagawa prefecture are available only the restoration curves of the Power delivery and City Gas delivery. In Figure 1 are shown the effects on the restoration curves of two main aftershocks, which occurred on April 7th (M=7.2) and on April 11th (M=7.0), on the different infrastructures and regions respectively. The first aftershock affected the most damaged regions located near the epicenter of the main shock and aftershock, whereas the second aftershock affected only the lifelines of Fukushima prefecture. City Gas delivery were not influenced from the two aftershocks in any region.

The method proposed in the paper for the evaluation of the interdependency index and the weights coefficients necessary to evaluate the regional resilience is based on the evaluation of the *CCF* among different restoration curves. In order to calculate the CCF functions, it is necessary that the time series would be at least weakly stationary (Shumway and Stoffer 2006). To minimize the effects of non-stationary and obtain meaningful statistical analyses, the time series data have been logarithmically transformed and second-differenced. This transformation stabilizes the variability, and the mean value which remains constant through the time while the auto-covariance values decay rapidly and only depends on the time-difference $h = t_1 - t_2$ between the data series, where t_1 and t_2 are arbitrary points in time (Shumway and Stoffer 2006). An example of the results of the transformation is shown in Figure 2a about Power delivery and water supply for Miyagi region.

EVALUATION OF INTERDEPENDENCY INDEX

In order to have a set of homogeneous curves with which is possible use the transformation mentioned in previous paragraph, it is necessary to normalize the available data of the restoration curves and linearly interpolate them.

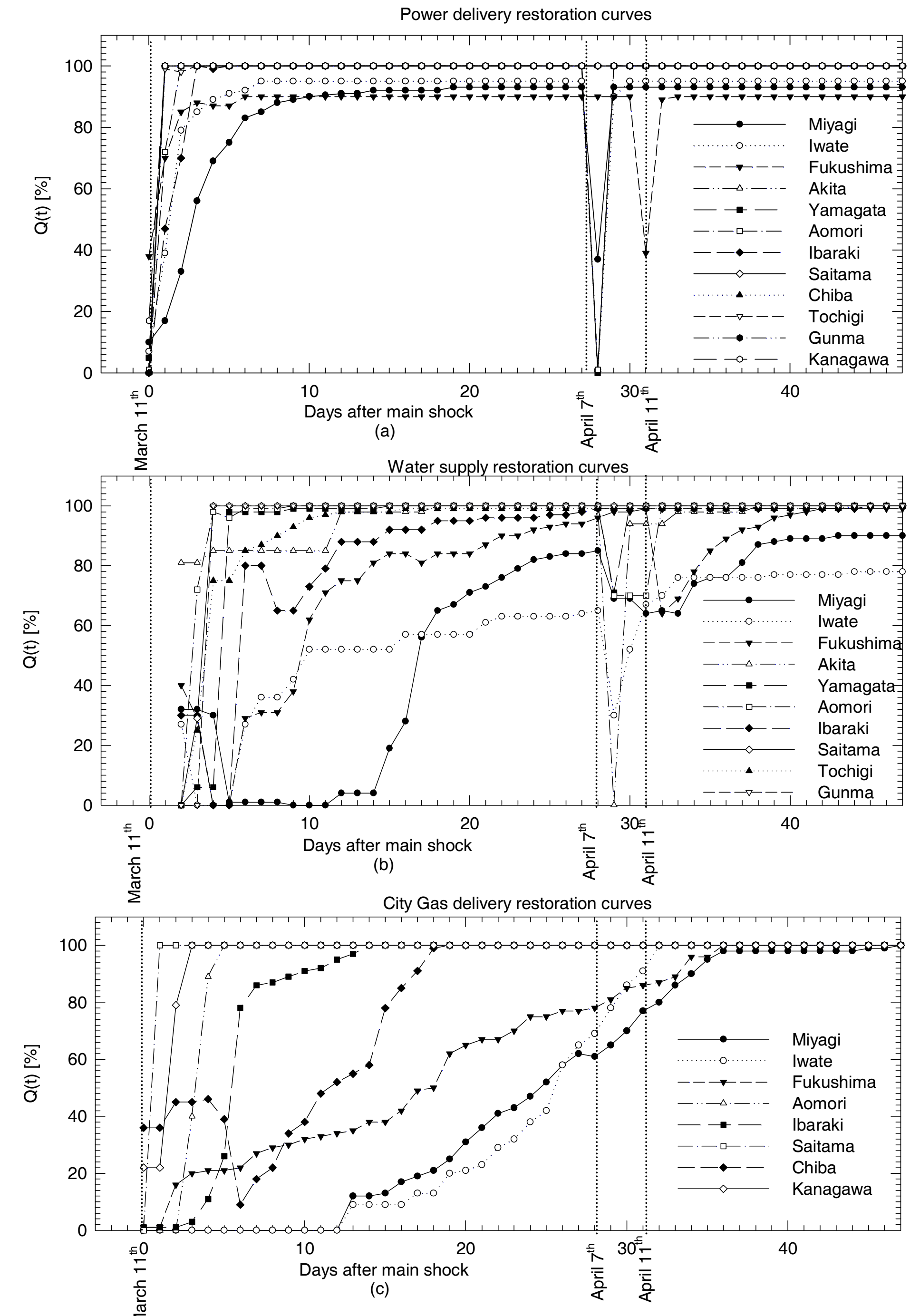

Figure 1 Restoration curves of different Regions of Japan after 2011-03-11 Mw =9.0 earthquake for three infrastructures: Power delivery (a), Water supply (b), City Gas delivery (c)

After the logarithmical transformation and the second-differenced of the data series, it is possible evaluate the CCF functions ($\rho_{i,j}(h)$) for different combinations of the restoration curves.

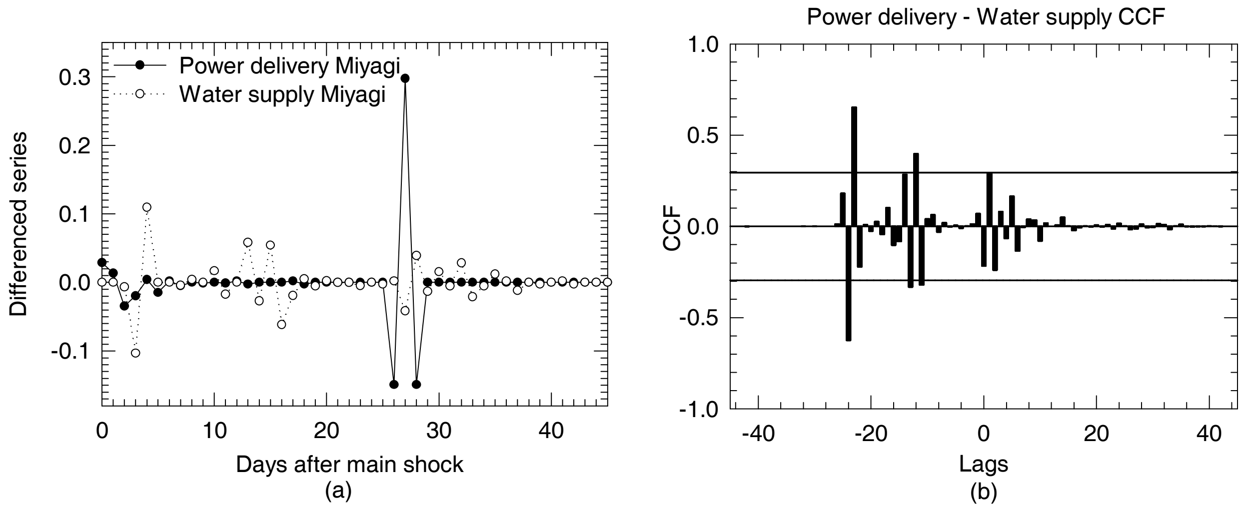

Figure 2 Miyagi power delivery and water supply restoration curves logarithmically transformed and second differenced (a); Cross correlation function of power delivery and water supply in Miyagi region (b).

In Figure 2b is shown an example of *CCF* function about *Power delivery* and *water supply* for Miyagi region. Three equations are proposed (Eq. 2, 3, 4), with which it is possible to evaluate the interdependence index ($S_{i,j}$) among different infrastructures and compared them with the results of Equation (1) which has been proposed by Dueñas-Osorio and Kwasinski (2012)

$$S_{i,j} = \begin{cases} \dfrac{\rho_{i,j}^{+}(h)}{1+\sqrt{|h|}} \times \mathrm{sgn}(h) & when \quad h \neq 0 \\ \rho_{i,j}^{+}(h) & when \quad h = 0 \end{cases} \tag{1}$$

where $\rho_{i,j}^{+}(h)$ corresponds to the maximum positive CCF value, which occurs at the peak lag time value h with absolute value $|h|$, and the sign function (*sgn*) is used to keep track of the dominant system in practice. The i^{th} system leads [lags] the restoration of the j^{th} system when $S_{i,j}$ is positive [negative] (Dueñas-Osorio and Kwasinski 2012).

$$S_{i,j} = \begin{cases} \dfrac{\rho_{i,j}^{+}(h)}{h} & when \quad h \neq 0 \\ \rho_{i,j}^{+}(h) & when \quad h = 0 \end{cases} \tag{2}$$

$$S_{i,j} = \frac{1}{N} \sum_{k=1}^{N} \left(\begin{cases} \dfrac{\rho^{\geq bound}(h_k)}{1+\sqrt{|h_k|}} \times \mathrm{sgn}(h_k) & when \quad h_k \neq 0 \\ \rho^{\geq bound}(h_k) & when \quad h_k = 0 \end{cases} \right) \tag{3}$$

$$S_{i,j} = \frac{1}{N}\sum_{k=1}^{N}\left(\begin{cases} \dfrac{\rho^{\geq bound}(h_k)}{h_k} & when \quad h_k \neq 0 \\ \rho^{\geq bound}(h_k) & when \quad h_k = 0 \end{cases}\right) \tag{4}$$

where $\rho^{\geq bound}(h_k)$ corresponds to the positive CCF values, at h_k lag time values, that exceed the threshold of statistical significance (the threshold is shown in Figure 2b with the two horizontal lines), N corresponds to the number of *CCF* values that exceed the upper bound of statistical significance. *n* infrastructure restoration curves are analyzed and the results are organized in a matrix of dimension $n \times n$ in which every elements ranges between -1 and 1. Positive values of this index shows that the i^{th} infrastructure (row) leads the restoration process of the j^{th} infrastructure (column), while negative value of this index shows that the i^{th} infrastructure (row) is lags behind the restoration process of the j^{th} infrastructure (column). The results of March 11th 2011 Tohoku Earthquake are shown in Table 1, while in Figure 3 are shown the comparison of different interdependency index $S_{i,j}$ proposed in the regions of Miyagi and Iwate respectively.

Table 1. Comparison of different interdependency indices from different equations

Region		S_{ij} Eq. (1) (Dueñas-Osorio and Kwasinski, 2012)	S_{ij} Eq. (2)	S_{ij} Eq. (3)	S_{ij} Eq. (4)
Miyagi	Power - Water	-0.11	-0.10	-0.03	-0.03
	Power - Gas	-0.15	-0.15	-0.05	-0.05
	Water - Gas	0.10	0.03	0.04	0.00
Iwate	Power - Water	0.33	0.07	0.66	0.21
	Power - Gas	-0.10	-0.13	-0.03	-0.08
	Water - Gas	-0.10	-0.04	-0.08	-0.03
Fukushima	Power - Water	0.22	0.04	0.44	0.14
	Power - Gas	-0.11	-0.10	-0.02	-0.03
	Water - Gas	-0.15	-0.15	-0.11	-0.11
Yamagata	Power - Water	-0.13	0.02	-0.03	0.16
Akita	Power - Water	0.46	0.46	0.93	0.93
Ibaraki	Power - Water	0.14	0.14	0.09	0.09
	Power - Gas	0.19	0.16	0.12	0.12
	Water - Gas	0.87	0.87	0.87	0.87
Tochigi	Power - Water	0.29	0.29	0.26	0.26
Aomori	Power - Water	-0.13	-0.13	-0.03	-0.03
	Power - Gas	-0.11	-0.11	-0.03	-0.03
	Water - Gas	0.72	0.72	0.72	0.72
Chiba	Power - Gas	0.15	0.15	0.11	0.11
Gunma	Power - Water	0.26	0.26	0.23	0.23
Saitama	Power - Water	0.29	0.29	0.27	0.27
	Power - Gas	1.00	1.00	1.00	1.00
	Water - Gas	-0.29	-0.29	-0.27	-0.27

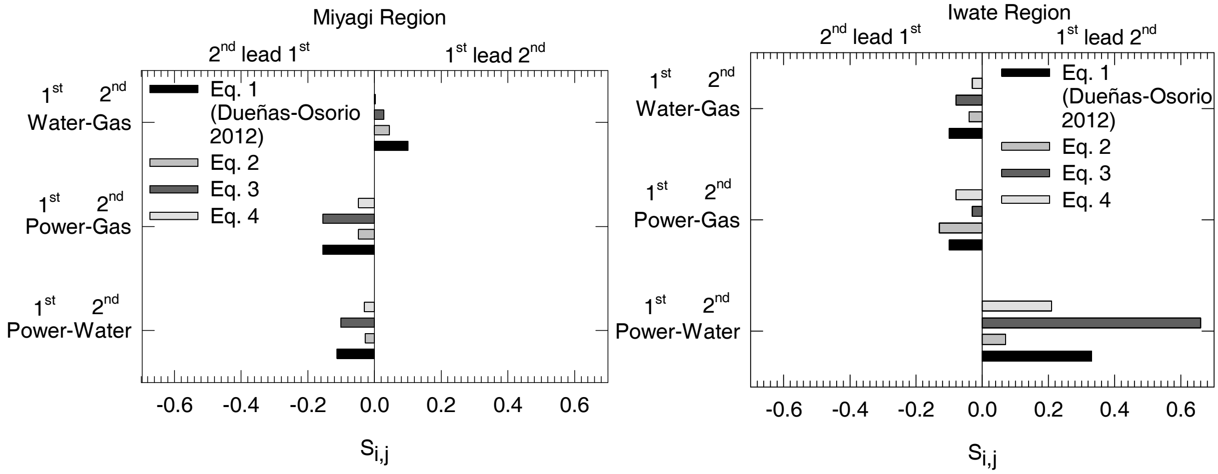

Figure 3 Miyagi and Iwate region: comparison of different interdependency index $S_{i,j}$ proposed models

CALCULATION OF THE WEIGHT COEFFICIENTS OF THE INFRASTRUCTURES

The weights w_i of the different infrastructures, which are necessary in order to assess the regional resilience, are calculated with the following equation:

$$w_i = \frac{\sigma_i}{\sum_i \sigma_i} \tag{5}$$

where σ_i is the sum of the positive values of the i^{th} row of the interdependence matrix $S_{i,j}$.

$$\sigma_i = \sum_j S_{i,j} \qquad when \quad S_{i,j} > 0 \tag{6}$$

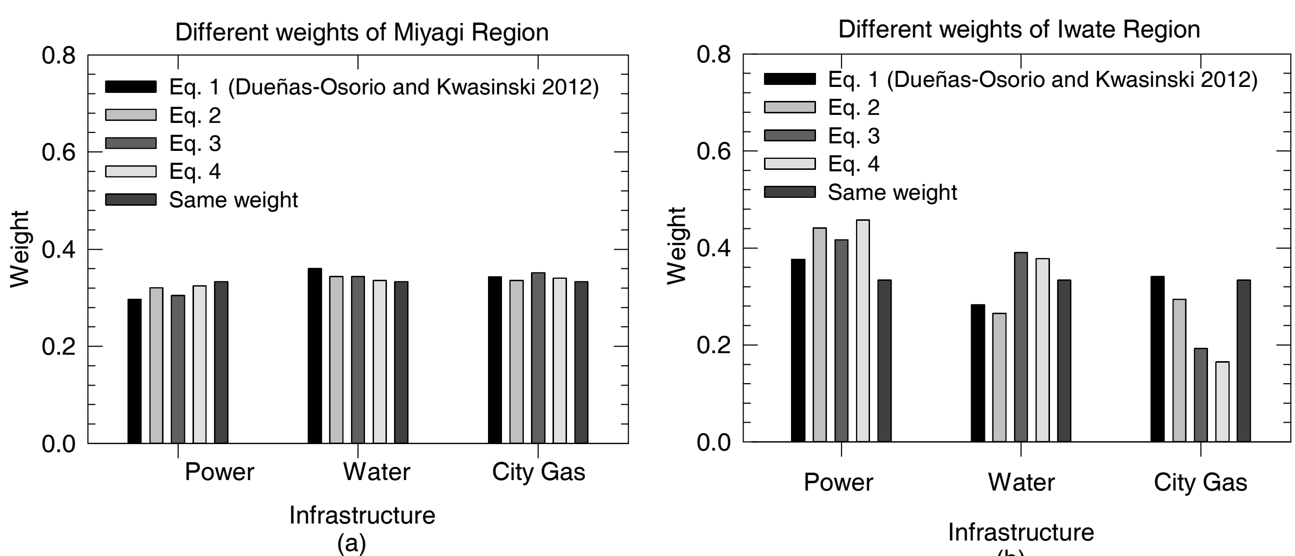

Figure 4 Comparison of different weights coefficients for Miyagi region (a) and for Iwate region (b) for the three different infrastructures

The different weight coefficients are evaluated for all the 12 Japanese prefectures affected by the 2011 earthquake and for the three lifelines using equations (1), (2), (3) and (4). Part of these results is shown in Figure 4 for Miyagi and Iwate prefectures.

REGIONAL RESILIENCE INDEX

The resilience of each infrastructure is given by the following equation (Cimellaro et al., 2010b, 2013a, 2013b):

$$R_i = \int_0^{T_c} \left(\frac{Q_i(t)}{T_c} \right) dt \tag{7}$$

where R_i is the value of resilience of the i^{th} infrastructure, $Q_i(t)$ is the functionality of the i^{th} infrastructure at time t, T_c is the control period that in this case is *47* days (the length of the available records of March 11th 2011 Tohoku Earthquake. The Regional resilience R is evaluated with Equation (8) using the weights of the different infrastructures calculated with Equation (5).

$$R = \sum_i \left(R_i \times w_i \right) \tag{8}$$

Results are shown in Table 2 and in Figure 5 for different weights of infrastructure's resilience.

Table 2. Regional Resilience index evaluated with different weights

Region	Eq.(1) (Dueñas-Osorio and Kwasinski 2012)	Eq.(2)	Eq.(3)	Eq.(4)	Same weight
Miyagi	0.61	0.62	0.62	0.62	0.63
Iwate	0.67	0.69	0.69	0.70	0.65
Fukushima	0.75	0.78	0.77	0.79	0.76
Yamagata	0.92	0.94	0.92	0.94	0.92
Akita	0.95	0.95	0.95	0.95	0.94
Ibaraki	0.88	0.87	0.88	0.87	0.89
Tochigi	0.94	0.94	0.94	0.94	0.94
Aomori	0.97	0.97	0.97	0.97	0.96
Chiba	0.90	0.90	0.89	0.89	0.89
Gunma	0.95	0.95	0.95	0.95	0.95
Saitama	0.93	0.93	0.93	0.93	0.93
Kanagawa	0.97	0.97	0.98	0.98	0.97

In Figure 5 it is shown that the major damage occurs in the regions near the epicenter of the main shock. The tsunami caused relevant damages (lower values of the resilience index) in the regions facing the Pacific coast (Miyagi, Iwate, Fukushima, Ibaraki, Aomori, Chiba, Kanagawa), even if they were far from the epicenter. For example, Chiba region has suffered more damage than Tochigi even if Chiba is more distant from the epicenter of the earthquake than Tochigi. This is because Chiba is on the Pacific coast while Tochigi is an interior region. In Figure 6 it is shown the standard deviation of the regional resilience index ordered for each region according to the distance from the epicenter. Near the epicenter are observed higher values of standard deviation which decreases far from it, with the exception of the region closest to the epicenter (Miyagi).

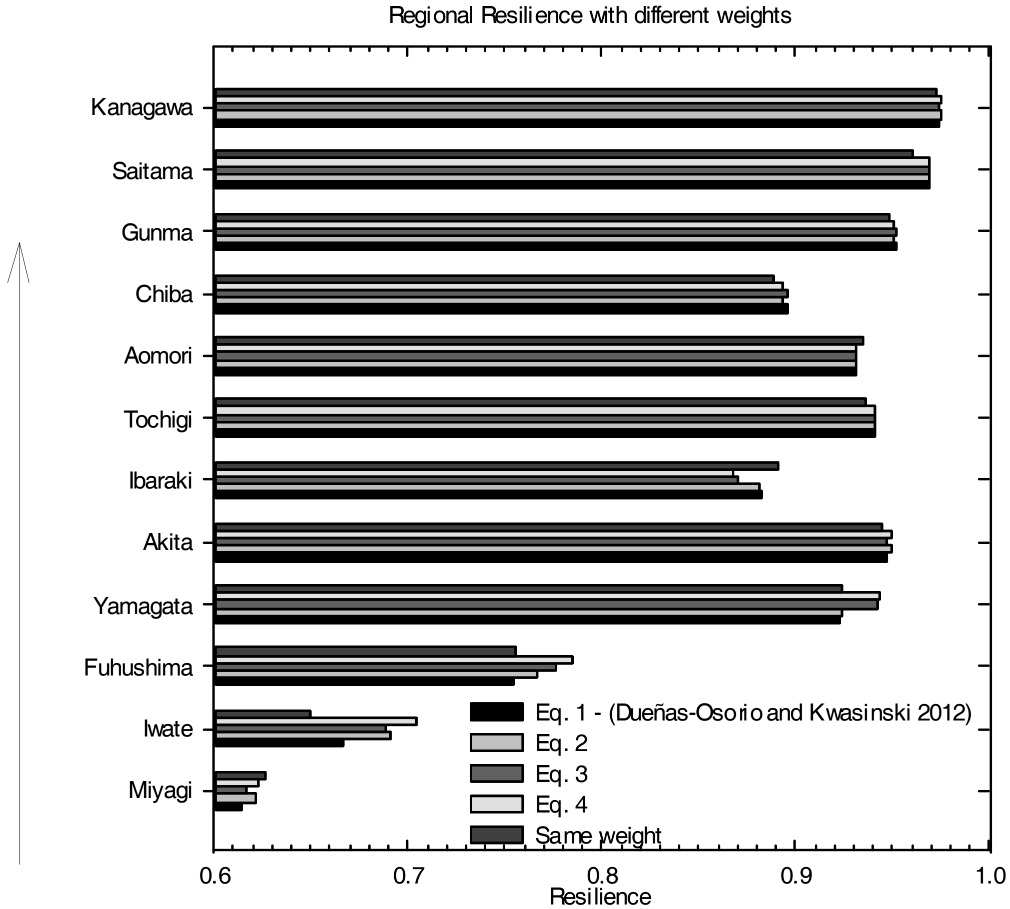

Figure 5 Regional resilience calculated using different weights starting from the resilience index of every infrastructure

Since the interdependency index ($S_{i,j}$) affects the weight values and then the final value of regional resilience index, it is important to find a proper methodology to evaluate it. Equations (1) and (3) have for denominator the term $1+\sqrt{|h|}$ that has the effect of amplifying the interdependency index with respect to equations(2) and (4) that have for the denominator term h (Figure 3). The equations that have for denominator $1+\sqrt{|h|}$ give more importance to the terms far from lag 0 with respect to the equations that have for denominator h, but if CCF function has a peak to lag ± 1, Equations (1) and (3) give a value of $S_{i,j}$ that is a half of that which would be obtained using Equations (2) and (4). In Figure 5 it is shown that the weight does not influence the values of the resilience index for regions far from the epicenter. The effect of weight coefficients on the resilience index also disappears in the regions where the epicenter of the earthquake was extremely close and where the tsunami has struck the coast with violence generating extreme damage and drop of functionality to zero such as in the Miyagi region.

Equation (4) tends to overestimate the value of resilience with respect to Equation (1) especially for the regions near the epicenter. Finally, in Figure 4b it is shown how Equation (4) (which takes into account all the *CCF* positive values over the threshold of statistical significance with their lags) gives to power delivery a higher weight with respect to others infrastructure. This behavior is given by the particular structure of the equation which tends to maximize the weight of the infrastructure that has a high value of *CCF* in correspondence to low positive lags (this is the characteristic of *CCF* function of power delivery restoration curves).

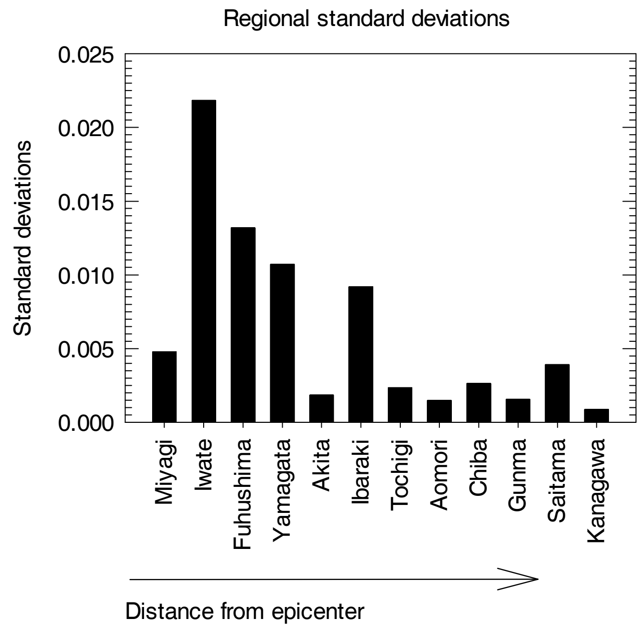

Figure 6 Standard deviation of regional resilience

This effect is more important for the regions near the epicenter and tends to become not relevant for regions far from it. This result has a physical meaning, because electric power has a large influence on other lifelines and tends to lead the restoration process or the cascading effects of all other infrastructures. All the others equations don't lead to this result. Based on the considerations above, Equation (4) has been adopted for the evaluation of interdependency index $S_{i,j}$. Figure 7 shows the prefectures of Japan and their corresponding value of regional resilience index obtained with the process illustrated in this article using Equation 4 to evaluate the weight coefficients.

REMARKS AND CONCLUSIONS

In this article it is proposed a method to evaluate the resilience index of a specific geographic area, by including lifelines' interdependency. Regional resilience is computed starting from a single regional infrastructures resilience which is combined with other infrastructure resilience index using weights coefficients, which are evaluated starting from the degree of interdependency. The degree of interdependency is evlauated starting from a new equation which is based on CCF functions among different restoration curves of different lifelines. Finally the procedure is adopted to the March 11th 2011 Tohoku Earthquake in Japan. Further detail about the methodology described in the paper can be found in Cimellaro and Solari, 2013c.

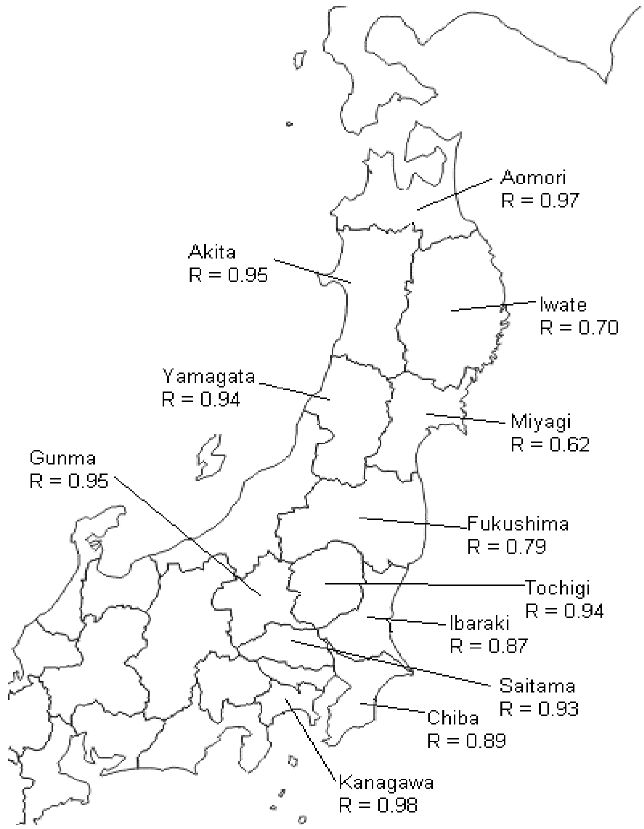

Figure 7 Regional resilience after the main shock evaluated using Equation (4) to evaluate the weight coefficients

ACKNOWLEDGEMENTS

The research leading to these results has also received funding from the European Community's Seventh Framework Programme - Marie Curie International Reintegration Actions - FP7/2007-2013 under the Grant Agreement n° PIRG06-GA-2009-256316 of the project ICRED - Integrated European Disaster Community Resilience.

REFERENCES

Arcidiacono, V., Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. "Community Resilience Evaluation including interdependencies." *15th World Conference on Earthquake Engineering (15WCEE)*, Lisbon, Portugal, September 24-28th, 2012.

Bigger, J. E., Willingham, M. G., Krimgold, F., and Mili, L. (2009). "Consequences of critical infrastructure interdependencies: lessons from the 2004 hurricane season in Florida." *Int. J. of Critical Infrastructures*, 5(3), 199-219.

Cimellaro, G. P., Villa, O., and Bruneau, M. (2013a). "Resilience-Based Design of Natural gas distribution networks." *Journal of Infrastructure Systems, ASCE*, in press.

Cimellaro, G. P. (2013b). "Computational framework for Resilience-Based Design (RBD) CH11." Seismic risk analysis and management of civil infrastructure systems, U. o. B. C. Edited by S Tesfamariam, Canada and K Goda, University of Bristol, UK, ed., Woodhead Publishing Limited, 80 High Street, Sawston, Cambridge, CB22 3HJ, UK, 810.

Cimellaro, G. P., Solari, D., and Bruneau, M. (2013c). "Regional Resilience of Japanese infrastructures during 2011 Great East Japan Earthquake " *Earthquake Spectra*, in review.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010a). "Framework for analytical quantification of disaster resilience." *Engineering Structures*, 32(11), 3639–3649.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010b). "Seismic resilience of a hospital system." *Structure and Infrastructure Engineering*, 6(1-2), 127-144.

Delamare, S., Diallo, A.-A., and Chaudet, C. (2009). "High-level modeling of critical infrastructures' interdependencies." *Int. J. of Critical Infrastructures*, 5(1/2), 100 - 119.

Duenas-Osorio, L., and Kwasinski, A. (2012). " Quantification of Lifeline System Interdependencies after the 27 February 2010 Mw 8.8 Offshore Maule, Chile, Earthquake. " *Earthquake Spectra,* V. 28, S1, S581–S603, June 2012.

Kjølle, G. H., Utne, I. B., and Gjerde, O. (2012). "Risk analysis of critical infrastructures emphasizing electricity supply and interdependencies." *Reliability Engineering & System Safety*, 105(0), 80-89.

Nojima, N. (2012). "Restoration Processes of Utility Lifelines in the Great East Japan Earthquake Disaster, 2011." 15th World Conference on Earthquake Engineering (15WCEE), Lisbon, Portugal, September 24-28, 2012.

Paton, D., and Johnston, D. (2006). "Disaster resilience an integrated approach." *Charles C Thomas publisher LTD.*, Cap. 4," lifelines and urban resilience".

Poljansek, K., Bono, F., and Gutierrez, E. (2012). "Seismic risk assessment of interdependent critical infrastructure systems: The case of European gas and electricity networks." *Earthquake Engineering & Structural Dynamics*, 41(1), 61-79.

Rinaldi, S., Peerenboom, J., and Kelly, T., 2001. "Identifying, understanding, and analyzing critical infrastructures interdependencies." *IEEE Control Systems Magazine* 21, 11–25.

Solari, D., and Cimellaro, G. P. (2013). "A comprehensive methodology for the evaluation of infrastructure interdependencies." 4th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN2013), Kos Island Greece, June 12-14th, 2013.

Shumway, R. H., and Stoffer, D. S. (2006). "Time Series Analysis and Its Applications.", *Springer*, New York, 596 pp.