COMPDYN 2011
ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25-28 May 2011

RESILIENCE-DRIVEN DISASTER MANAGEMENT OF CIVIL INFRASTRUCTURE

Paolo Bocchini and Dan M. Frangopol

Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center
Department of Civil and Environmental Engineering
Lehigh University
117 ATLSS Dr., Bethlehem, PA 18015, USA
e-mail: {paolo.bocchini, dan.frangopol}@lehigh.edu

Keywords: Resilience, Disaster Management, Optimization, Bridge Networks, Distributed Civil Infrastructure Systems.

Abstract. *After the occurrence of a natural (e.g. earthquake, hurricane, flood, fire) or technological (e.g. explosion, terrorist attack) extreme event, the distributed infrastructure systems and their individual structural components are likely to be significantly damaged. For the emergency response and the quick socio-economic recovery of the region, transportation networks, lifelines, and infrastructure in general play a role of utmost importance. For this reason, the so called "disaster management" has always to be focused on restoring as quickly as possible the proper functionality of the infrastructure under limited financial resources and other logistic constraints. The main focus of the present paper is to address this problem and provide a general framework to assist the decision making process in these critical situations. In fact, the main issue in these scenarios is to have a practical and robust way to collect and analyze data with a fast and reliable tool that can lead to quick but informed decisions.*

Several decision support systems for emergency and/or disaster management have been proposed in the last decades. The proposed approach is based on the holistic concept of resilience, which is gaining momentum as metric for the evaluation of the efficiency of the restoration activities. Resilience is used in this paper as one of the optimization criteria for the rehabilitation planning.

An illustrative example is presented to clarify the applicability of the proposed approach to transportation networks.

1 INTRODUCTION

Lately, the concept of resilience and the interest on its possible practical applications is gaining a lot of momentum. "Resilience" has become a very popular keyword for articles, symposia, workgroups, special sessions, research projects, and, in general, in the press. I civil engineering, the use of resilience is associated with disaster loss mitigation and disaster management [1, 2], especially for analyses of distributed civil infrastructure systems [3, 4] and lifelines [5].

This paper promotes a novel paradigm for the resilience-driven disaster management of civil infrastructure, with application to bridge networks. A multi-criteria perspective is proposed as optimal way to develop a framework for the quantitative assessment of resilience and its use for assisted decision making in the disaster management practice [6].

In the past years, several *systemic* definitions of resilience and frameworks for its use have been proposed. Some of the most comprehensive can be found in [7, 8, 9, 10, 11], while Rose [12] presents an interesting review of possible definitions. Section 2 focuses on the *analytical* definitions of resilience, with particular emphasis on the family of the formulation that is used in this paper. Section 3 describes the proposed multi-objective approach. Section 4 presents an illustrative example involving the post-disaster restoration of a bridge network. Finally, Section 5 collects the concluding remarks.

2 ANALYTICAL DEFINITIONS OF RESILIENCE

In the literature, several analytical definitions of resilience have been proposed and applied. Zhou et al. [13] have collected a list where the first definition of resilience dates back to 1973 [14]. The first seed of the definition of resilience that is most popular nowadays can be found in [15]: "Resilience is the ability of human communities to withstand external shocks or perturbations to their infrastructure and to recover from such perturbations". Along the decades, several authors have focused on one or more aspects of resilience, such as the ability of a structure or system to withstand an extreme event (better called "capacity" for structural applications) or the time required to recover the original functionality (sometimes referred to as "rapidity"). In 2003, a large group of researchers introduced the concept of "resilience triangle", to combine the various aspects associated with resilience [16]. The resilience triangle was originally used to describe the "loss of resilience" and was associated with the equation:

$$R_1 = \int_{t_0}^{t_r} [100 - Q(t)] \, \mathrm{d}t \tag{1}$$

where R_1 is the loss of resilience experienced by the system, t_0 is the time instant when the extreme event occurs, t_r is the time when the functionality of the infrastructure is fully restored, Q is the percentage "functionality" (or "quality", or "serviceability") of the system, and t is time. Figure 1 shows a graphical interpretation of the resilience triangle and of the resilience loss R_1 in Eq. (1). The definition in Eq. (1) has the merit of connecting analytically the concepts of resilience and functionality and has been used in several subsequent articles [17, 18, 19].

Cimellaro et al. [20, 21] proposed a different analytical formulation that focused on resilience itself, rather than on its loss:

$$R_2 = \int_{t_0}^{t_r} Q(t) \, \mathrm{d}t \tag{2}$$

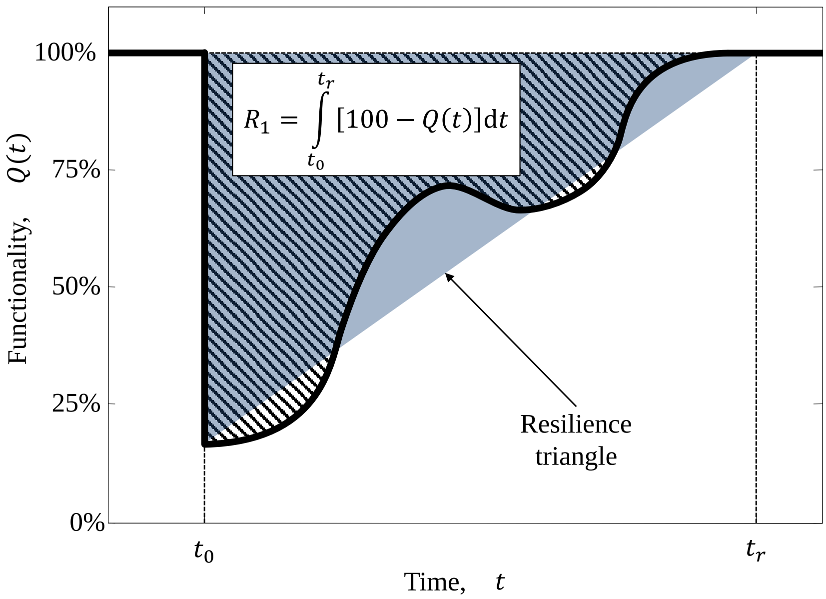

Figure 1: Resilience triangle (shaded) and resilience loss R_1 (diagonal partern).

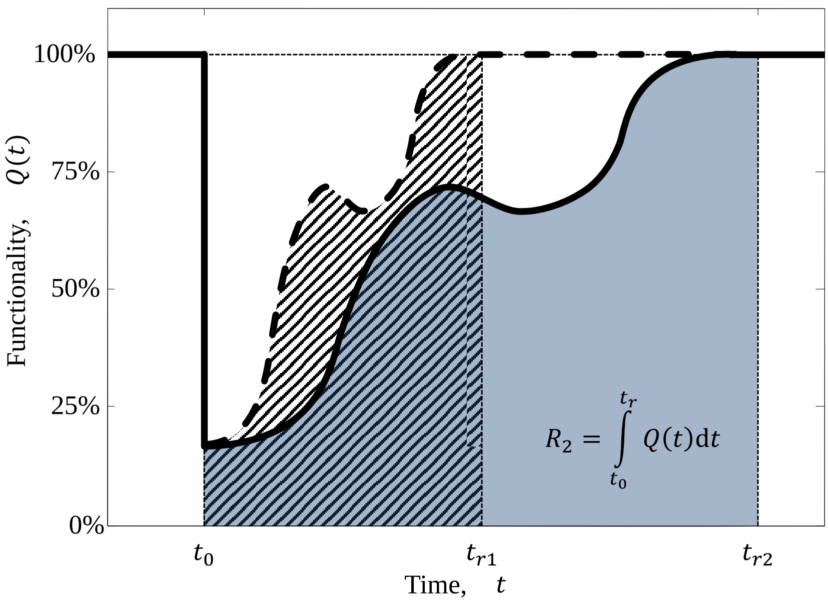

Figure 2: Resilience according to Eq. (2). The faster recovery path (dashed) yields a lower value of resilience (area with diagonal pattern) than the slower recovery path (solid).

This definition branches out from the resilience triangle and has the advantage of being able to take into account restoration patterns that bring the final functionality to a level different (i.e. lower or even higher) from 100%. However, Eq. (2) has a drawback that makes it inappropriate for some applications. In fact, the integral is computed between t_0 and t_r and this can result in low values of resilience for fast restoration strategies (see Figure 2).

To overcome the mentioned issue, Bocchini and Frangopol [22] proposed to modify the

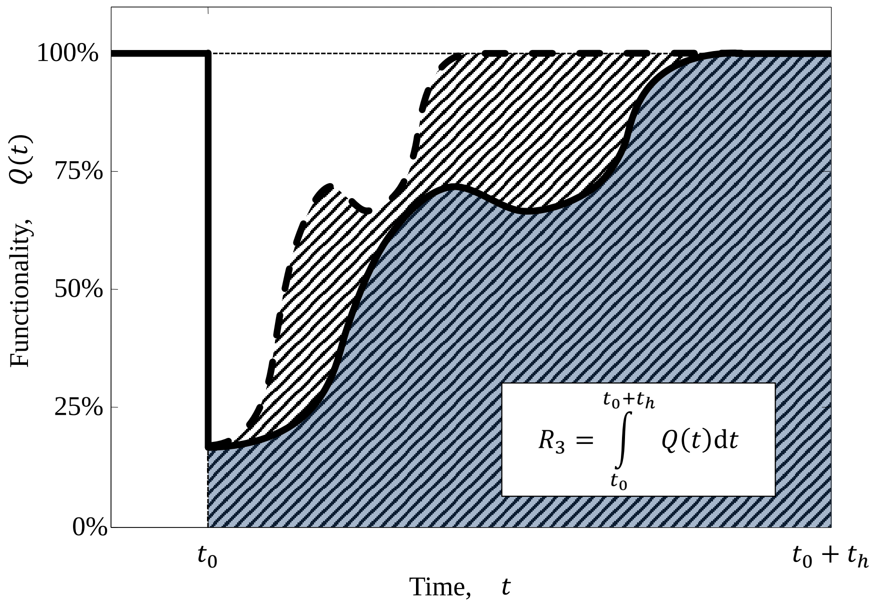

Figure 3: Resilience according to Eq. (3). The faster recovery path (dashed) correctly yields a higher value of resilience (area with diagonal pattern) than the slower recovery path (solid).

analytical definition of resilience, focusing on a fixed time horizon t_h:

$$R_3 = \int_{t_0}^{t_0+t_h} Q(t)\,\mathrm{d}t \tag{3}$$

Figure 3 shows that this definition correctly provides higher (i.e. better) values of resilience for the faster (i.e. better) recovery paths. The definition in Eq. (3) can be used to compare, rank, and optimize [22] the various disaster management strategies. The investigated time horizon t_h does not need to be chosen larger than the longest recovery time. In fact, if the recovery is not complete at $t = t_0 + t_h$, Eq. (3) is still applicable and yields, as expected, a small value of resilience. Unfortunately, R_3 still shares a shortcoming with R_1 and R_2: in all these cases resilience is measured in units of time, since $Q(t)$ is non-dimensional. Despite the fact that Eq. (3) computes correct values of resilience, these values expressed in units of time can be difficult to interpret and communicate to decision makers.

For this reason, a normalization factor was later introduced [4, 23]:

$$R_4 = \frac{\int_{t_0}^{t_0+t_h} Q(t)\,\mathrm{d}t}{t_h} \tag{4}$$

The numerator of Eq. (4) represents the area underneath the recovery path $Q(t)$; the denominator represents the value of resilience in case the event did not occur or had no effects on functionality (i.e. $100\% \cdot t_h = t_h$). Figure 4 provides a graphical interpretation of Eq. (4).

Depending on the general frameworks and applications where the analytical definitions of resilience in Eqs. (1)–(4) are used, each of them can be appropriate. However, R_4 is the most versatile and easy to use for decision makers.

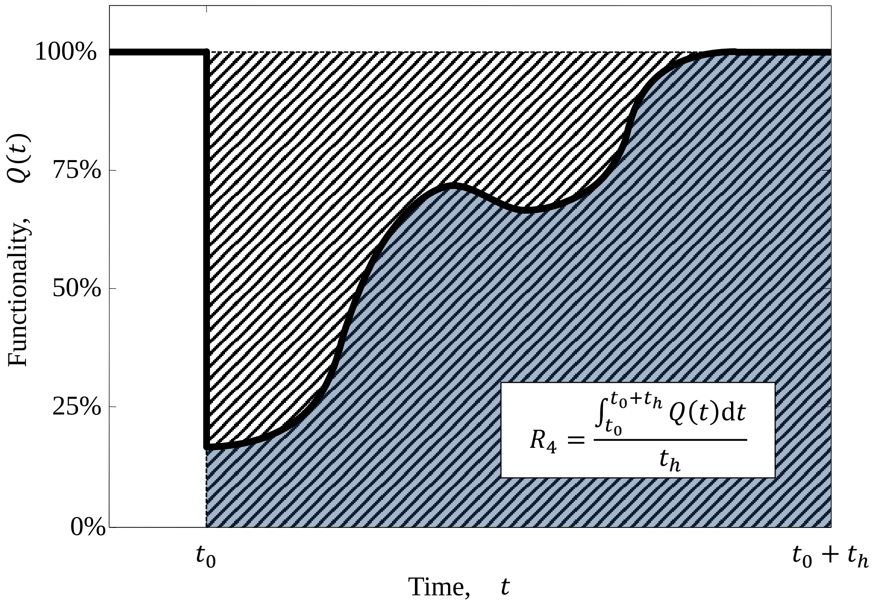

Figure 4: Resilience according to Eq. (4). The numerator of Eq. (4) is the shaded area, the denominator is the area of the large rectangle (area with diagonal pattern).

3 MULTI-CRITERIA PERSPECTIVE

Resilience is a concept that intrinsically includes several metrics. For instance, Bruneau et al. [16] define the four "properties" of resilience (i.e. "robustness", "rapidity", "redundancy", and "resourcefulness") and the four "dimensions" of resilience (i.e. "technical", "organizational", "social", and "economic"). The need of capturing all these aspects has led researchers to pursue two conflicting objectives: (i) on one hand the desire of having a synthetic, scalar index of resilience, for immediate comparison and ranking of different strategies; (ii) on the other hand the goal of representing, within a single concept, a broad set of "properties" and "dimensions". In this paper, it is proposed to reconcile these two conflicting objectives by means of a multi-criteria analysis and Pareto optimization.

Chang and Shinozuka [5] combined the concept of the resilience triangle with a probabilistic approach. To do this, they had to deviate from the basic definition in Eq. 1 and introduce acceptable thresholds for the post-event functionality $Q(t_0)$ and for the time to complete recovery t_r. This can be interpreted as a first attempt to introduce two criteria in the analysis and treat them as two separate limit states.

Similarly, Zobel [24] critics the fact that all the analytical definitions of resilience can yield the same value for very different scenarios in terms of initial loss and time to recovery, and this can be unacceptable or misleading for decision makers. Therefore, Zobel [24] proposes an "adjusted resilience function" that incorporates information on the relative importance of the time to complete recovery and the initial functionality loss, as perceived by decision makers.

The proposed approach consists in leaving the values of the important variables of the problem as separate metrics and combining them in the framework of Pareto optimization. In this way, the term "resilience" can be used to refer to the well-defined indicator R_4 in Eq. (4). Therefore, the search for the best recovery strategy should include resilience as one of its objectives, together with other objectives and constraints. For instance, for the case of disaster management of the civil infrastructure, the conflicting objectives are resilience [22], total cost of interventions [22], time to reach a target functionality level [25], and time to complete recovery [25]. As expected, resilience should be maximized, while the other values should be minimized. Moreover, Pareto optimization allows to introduce separate constraints and requirements, such as maximum cost of the interventions [22], minimum required functionality at a specific time instant [25], maximum number of simultaneous interventions on the components of a distributed system [23], and additional constraints on the individual restoration parameters. Therefore, given all the required data that depend on the specific application, the general optimization problem can be formulated as:

Find:

$$\text{parameters of the rehabilitation strategy} \tag{5}$$

so that

$$R = \text{maximum} \tag{6}$$
$$C = \text{minimum} \tag{7}$$
$$T_i = \text{minimum} \qquad \forall\ i = 1, 2, \ldots, I \tag{8}$$
$$T = \text{minimum} \tag{9}$$

subject to the constraints

$$C \leq C_{max} \tag{10}$$
$$Q(t_h^T) \geq Q_h^T \qquad \forall\ h = 1, 2, \ldots, H \tag{11}$$
$$N_{SI}(t) \leq N_{SI\ max} \qquad \forall\ t \in [t_0, t_0 + t_h] \tag{12}$$
$$\text{and constraints on the individual rehabilitation parameters} \tag{13}$$

where R is the resilience of the system, C is the total cost of the restoration interventions, T_i is the time required to reach target functionality level Q_i, T is the time of total recovery, C_{max} is the amount of available funding, Q_h^T is the target functionality level that must necessarily be provided at time t_h^T, N_{SI} is the number of simultaneous rehabilitation interventions applied to the system, and $N_{SI\ max}$ is the maximum allowable number of simultaneous interventions.

4 ILLUSTRATIVE EXAMPLE

The case of the post-disaster restoration of a bridge network is considered as a qualitative example. The functionality of the network $Q(t)$ is defined as its ability to effectively redistribute traffic flows and is a function of the total travel time spent and total travel distance covered by the network users that depart during a fixed peak traffic hour [22]. The rehabilitation strategies consist in the schedules of the interventions on the various bridges and the amount of funding invested on each bridge which, in turn, determines the quality and speed of the restoration [22].

The objectives are the maximization of the resilience R, defined as in Eq. (4), the minimization of the total cost of interventions C, the minimization of the time T_1 required to reach the functionality level $Q_1 = 50\%$, and the minimization of the total recovery time T.

The total restoration cost cannot exceed the maximum amount of funding C_{max}. Moreover, constraints on the minimum functionality level (Q_1^T and Q_2^T) at two time instants (t_1^T and t_2^T) are implemented. Finally, it is assumed that the maximum number of bridges that can undergo simultaneous interventions is $N_{SI\ max} = 5$.

Three restoration strategies are considered (namely, strategy A, B, and C) and their expected recovery paths are represented in Figure 5. All the strategies are associated with similar values

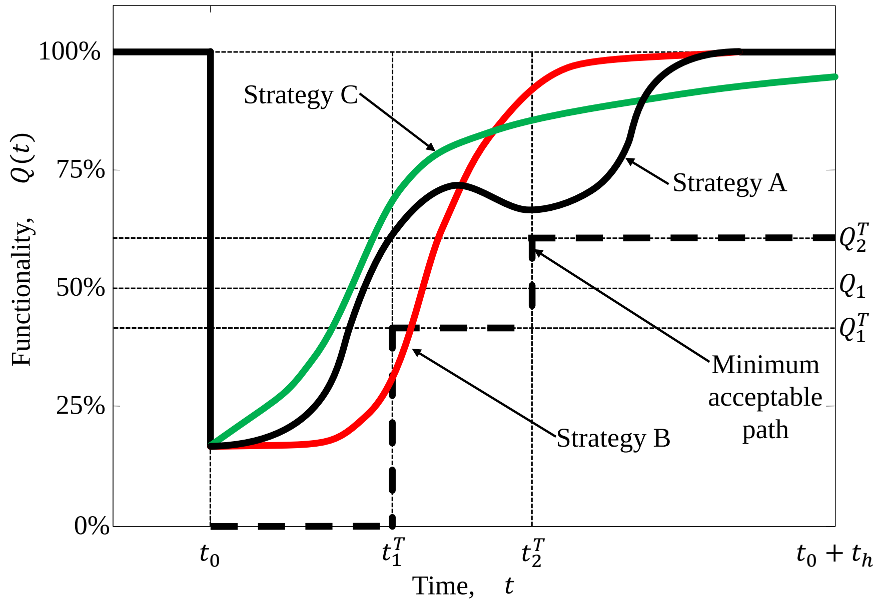

Figure 5: Three possible recovery strategies associated with similar values of resilience.

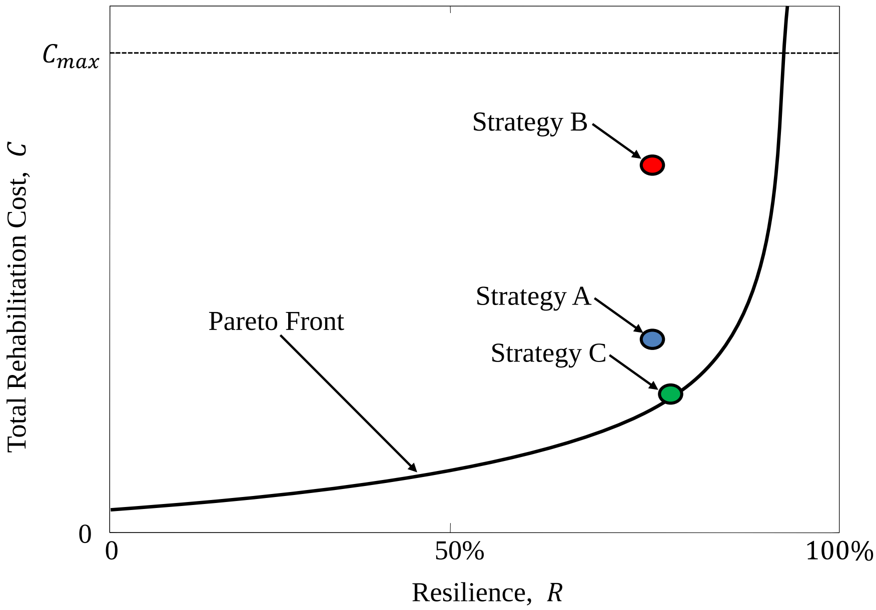

Figure 6: Pareto front in the plane of resilience and cost.

of resilience, defined by Eq. (4). Strategy A is characterized by a reduction of the functionality around time t_2^T. This usually happens when interventions start on some major bridges, requiring a (further) reduction of their flow capacity. It would be desirable to avoid negative slopes in the recovery path, and this can be required adding a constraint on the derivative of $Q(t)$. Nevertheless, strategy A yields a good value of resilience, is compatible with the requirements on the minimum functionality levels at t_1^T and t_2^T, makes the network reach $Q_1 = 50\%$ in a very short time, and the total restoration is completed significantly before the end of investigated time horizon. Strategy B has the same total recovery time as strategy A and a very similar overall

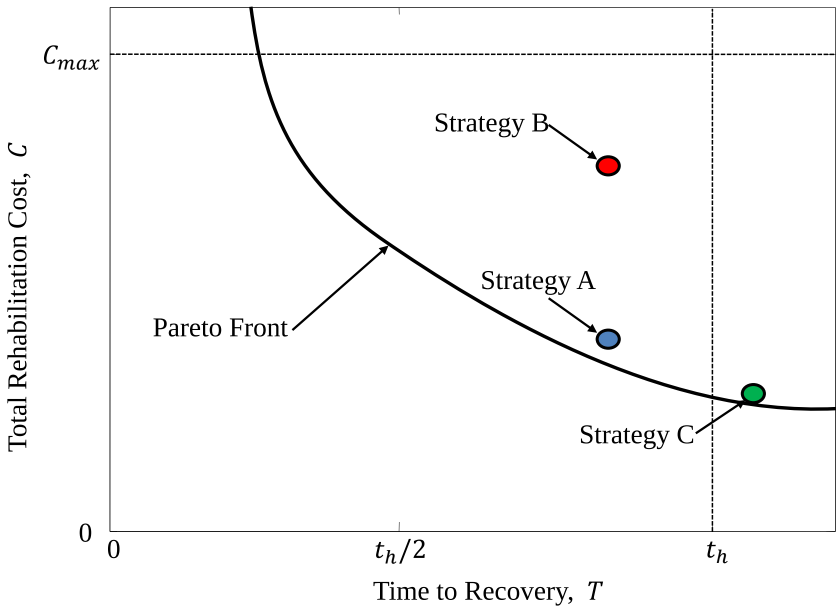

Figure 7: Pareto front in the plane of time to recovery and cost.

resilience. However, strategy B is not compliant with the constraint at time t_1^T (it crosses the dashed line, that represents the minimum required functionality in Figure 5). For this reason, strategy B should be discarded. Strategy C provides a very quick initial phase of the restoration activities and makes the network reach the values $Q_1 = 50\%$ in the shortest time, compared to the other strategies. Strategy C is also compliant with the constraints at t_1^T and t_2^T and provides a value of resilience that is slightly larger than the other strategies. This is achieved despite the fact that adopting strategy C, the network functionality is not entirely restored during the investigated time horizon: $Q(t_0 + t_h) < 100\%; \quad T > t_h$.

Figure 6 shows the Pareto front in the space of the two objectives resilience and total rehabilitation cost. A solution is said to be “Pareto-optimal” if there is no other solution that yields an improvement in one of the objectives, without worsening at least another. The front shows that to achieve higher values of resilience, more financial resources are required. All the strategies have a total rehabilitation cost that is lower than the available funding. Strategy C, in particular, requires the lowest investment and is on the Pareto front. It is very common that solutions that do not restore the entire functionality are very economical. In fact, avoiding a few very expensive bridge rehabilitation can determine a significant reduction in the cost, with a very small loss of the overall network functionality.

Figure 7 presents the Pareto front in the space of time to recovery and cost. As already mentioned, strategies A and B have very similar recovery times, while strategy C restores the entire functionality only after the end of the investigated time horizon. In this case both strategies A and C are very close to the Pareto front.

Similar plots in the spaces of the other objectives and of the design variables can be provided. Depending on the relative importance of the various objectives for the specific scenario, decision makers will choose the most convenient solution. For this example, strategy C seems to be the best compromise, for the reasons explained previously.

The procedure presented in this illustrative example can be automated by means of multi-objective genetic algorithms [26]. Numerical applications of the proposed approach to realistic bridge networks, solved by means of an automated procedure based on genetic algorithms can be found in [22, 23, 25].

5 CONCLUSIONS

A resilience-driven approach to the disaster management of the civil infrastructure has been presented. A new paradigm to the use of resilience is proposed, where resilience is one of the objectives in a multi-criteria analysis aimed at finding the best recovery path and the associated intervention strategy.

In the past, the intrinsic holistic nature of the concept of resilience has created a contrast between its *systemic definitions* (that try to be as comprehensive as possible) and its *analytical definitions* (that pursue a single scalar metric). In the proposed approach, a consistent resilience indicator is used in conjunction with other metrics and constraints that together define the best disaster management strategy. This approach reconciles the two diverging needs mentioned previously.

The framework of multi-criteria Pareto optimization appears to be the perfect paradigm to develop studies on resilience and disaster management within this novel perspective.

AKNOWLEDGMENTS

The support from (a) the National Science Foundation through grant CMS-0639428, (b) the Commonwealth of Pennsylvania, Department of Community and Economic Development, through the Pennsylvania Infrastructure Technology Alliance (PITA), (c) the U.S. Federal Highway Administration Cooperative Agreement Award DTFH61-07-H-00040, and (d) the U.S. Office of Naval Research Contract Number N-00014-08-0188 is gratefully acknowledged. The opinions and conclusions presented in this paper are those of the writers and do not necessarily reflect the views of the sponsoring organizations.

REFERENCES

[1] W. N. Carter, *Disaster management: a disaster manager's handbook*. Asian Development Bank, 1992.

[2] D. P. Coppola, *Introduction to international disaster management*. Butterworth Heinemann, 2007.

[3] D. M. Frangopol, P. Bocchini, Bridge network performance, maintenance, and optimization under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering*, in press, 2011.

[4] G. P. Cimellaro, , A. M. Reinhorn, M. Bruneau, Framework for analytical quantification of disaster resilience. *Engineering Structures*, **32**, 3639–3649, 2010.

[5] S. Chang, M. Shinozuka, Measuring improvements in the disaster resilience of communities. *Earthquake Spectra*, **20**, 739–755, 2004.

[6] W. A. Wallace, F. D. Balogh, Decision Support Systems for Disaster Management. *Public Administration Review*, **45**, 134–146, 1985.

[7] A. Rose, S. Y. Liao, Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions. *Journal of Regional Science*, **45**, 75–112, 2005.

[8] S. B. Miles, S. E. Chang, Modeling Community Recovery from Earthquakes. *Earthquake Spectra*, **22**, 439–458, 2006.

[9] Z. Çağnan, R. A. Davidson, S. D. Guikema, Post-Earthquake Restoration Planning for Los Angeles Electric Power. *Earthquake Spectra*, **22**, 589–608, 2006.

[10] M. Bruneau, A. Filiatrault, G. Lee, T. O'Rourke, A. Reinhorn, , M. Shinozuka, K. Tierney, *White Paper on the SDR Grand Challenges for Disaster Reduction*. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, The State University of New York, 2007.

[11] N. Xu, S. D. Guikema, R. A. Davidson, L. K. Nozick, Z. Çağnan, K. Vaziri, Optimizing scheduling of post-earthquake electric power restoration tasks. *Earthquake Engineering & Structural Dynamics*, **36**, 265–284, 2007.

[12] A. Rose, Defining and measuring economic resilience to disasters. *Disaster Prevention and Management*, **13**, 307–314, 2004.

[13] H. Zhou, J. Wang, J. Wan, H. Jia, Resilience to natural hazards: a geographic perspective. *Natural Hazards*, **53**, 21-41, 2010.

[14] C. S. Holling, Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, **4**, 1–23, 1973.

[15] P. Timmerman, Vulnerability. Resilience and the collapse of socieiy: A review of models and possible climatic applications. *Environmental Monograph, Institute for Environmental Studies, University of Toronto*, **1**, 1981.

[16] M. Bruneau, S. E. Chang, R. T. Eguchi, G. C. Lee, T. D. O'Rourke, A. M. Reinhorn, M. Shinozuka, K. Tierney, W. A. Wallace, D. V. Winterfeldt, A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra*, **19**, 733–752, 2003.

[17] M. Bruneau, A. M. Reinhorn, Overview of the resilience concept. *Proceedings of the* 8^{th} *National Conference of Earthquake Engineering*, San Francisco, CA, April 18–22, 2006.

[18] M. Bruneau, A. Reinhorn, Exploring the concept of seismic resilience for acute care facilities. *Earthquake Spectra*, **23**, 41–62, 2007.

[19] M. Bruneau, Enhancing the Resilience of Communities Against Extreme Events from an Earthquake Engineering Perspective. *Journal of Security Education*, **1**, 159–167, 2006.

[20] G. P. Cimellaro, A. M. Reinhorn, M. Bruneau, Quantification of seismic resilience. *Proceedings of the* 8^{th} *National Conference of Earthquake Engineering*, San Francisco, CA, April 18–22, 2006.

[21] G. P. Cimellaro, A. M. Reinhorn, M. Bruneau, Seismic resilience of a hospital system. *Structure and Infrastructure Engineering*, **6**, 127–144, 2010.

[22] P. Bocchini, D. M. Frangopol, Optimal resilience- and cost-based post-disaster intervention prioritization for bridges along a highway segment. *Journal of Bridge Engineering, ASCE*, in press and already available on line, DOI: 10.1061/(ASCE)BE.1943-5592.0000201, 2011.

[23] D. M. Frangopol, P. Bocchini, Resilience as optimization criterion for the rehabilitation of bridges belonging to a transportation network subject to earthquake. *Proceedings of the 2011 SEI-ASCE Structures Congress*, Las Vegas, NV, April 14–16, 2011.

[24] C. W. Zobel, Representing perceived tradeoffs in defining disaster resilience. *Decision Support Systems*, **50**, 394–403, 2011.

[25] P. Bocchini, D. M. Frangopol, Restoration of bridge networks after an earthquake: multi-criteria intervention optimization. *Earthquake Spectra*, Under review.

[26] K. Deb, *Multi-objective optimization using evolutionary algorithms*. John Wiley and Sons, 2001.