Resilience and Vulnerability of Spatial Economic Networks

Simone Caschili · Aura Reggiani · Francesca Medda

According to the Annual Disaster Statistical Review of 2012, the average number of naturally-triggered disasters occurring within a period of 1 year is about 300 events, in which over 100,000 people are killed as a consequence of their impacts. The statistics of disasters shed light on important trends arising, of which the two most salient are that developing and emerging economies suffer the most from human losses, and that the costs of natural disasters are escalating over time. In 2012 the Hurricane Sandy, one of the most ever expensive natural disasters in the United States, created damages for approximately US$ 50.0 billion (Guha-Sapir et al. 2013). Both natural and man-made disasters may have various spatial effects (from local to global scales) which reverberate for hours and even years when the damages affect the backbone of a system. Thus investigating these phenomena represent a complex but compelling issue. In the aim to predict and minimise the substantial economic losses generated by disruptive events, the attention of scholars, practitioners and policy makers is nowadays turning squarely toward such concepts as resilience, vulnerability, robustness, and reliability of economic spatial systems (Rose 2009).

In essence, resilience refers to the capacity of a network: a) to retain its organizational structure following the perturbation of some state variable from a given value; b) to adapt itself to new states; thus evolution is formed by the switch of these resilient networks from one equilibrium state to another. These definitions stem from ecology (for a review, Reggiani et al. 2002). The main question is then how fast and efficiently the network returns/shifts to steady states. Vulnerability research stems, by contrast, from hazard studies in geophysical/social sciences and in political economy/ecology.

S. Caschili (✉) · F. Medda
UCL QASER Laboratory, University College London, London, UK
e-mail: simon.caschili@gmail.com

F. Medda
e-mail: f.medda@ucl.ac.uk

A. Reggiani
Department of Economics, University of Bologna, Bologna, Italy
e-mail: aura.reggiani@unibo.it

The two concepts are not strictly inversely related; they can be complementary (Miller et al. 2010). In other words, resilience is the responsiveness of the network after a shock, while vulnerability is about the condition, the susceptibility of the network, rather than a direct outcome of a perturbation (Seeliger and Turok 2013). The main research question is then whether a *complex network is* a necessary condition for the presence or detection of *resilience and vulnerability.*

Within this context, network theory has progressively become the paradigm that scholars use to study the propagation of favourable and disruptive events connected to networks' evolution and shock propagation. The network theory paradigm is important because it allows for the creation of a schematic and systemic approach to the interdependency and interconnection of social, economic and infrastructure spatial networks. The space – considered as *action container* – plays a significant role in this respect because within 'spatial economics' we are able to merge space and economic processes (Nijkamp and Ratajczak 2013). Spatial settings are thus composed of complex interconnected systems characterised by high levels of uncertainty. Uncertainty is therefore at the core of the attention paid to system resilience and vulnerability (Modica and Reggiani, in this Special Issue).

This Special Issue (SI) brings 'under one roof' the work of scholars dedicated to the resilience and vulnerability of systems. Three main strands knit the different contributions together, and constitute the rationale for their selection in this volume: a) resilience/vulnerability; b) dynamic (complex) networks; and c) space-economy. In particular this SI provides a synthetic perspective on the various interpretations of resilience and vulnerability in spatial economic networks, given the different objectives and landscapes, with special attention to the understanding of the effects generated by disruptions of spatial economic systems. Consequently, the selection of articles in this SI offers novel theoretical and empirical insights into the complex dynamics of economic and spatial networks, using new, systematic data sources and employing cutting-edge network analysis and spatial econometric techniques. Within this framework, the chosen contributions analyse transport networks and economic networks – at various spatial scales – with the view to identifying the critical factors that lead to resilient and vulnerable outcomes.

The contributions here have been selected (and peer-reviewed) from among the papers presented at the Special Session on "Resilience and Vulnerability in Complex Spatial Networks," organized by Aura Reggiani, Francesca Medda and Simone Caschili, under the aegis of the 12th International NECTAR Conference held in Säo Miguel Island (Azores, Portugal) on 16–18 June, 2013. Table 1 summarises the main features of the papers:

- *Transportation/Economic System* indicates whether the paper focuses on transportation and/or economic systems.
- *Country* elucidates the national context under analysis.
- *Spatial Scale* refers to different spatial contexts: cities, regions and communities, as well as organisations of firms.
- *Spatial/Economic Variable* refers to the categories of variables included in the models.
- *Time period* reports the period of reference of the study.
- *Methodology* indicates the analytical tools applied in the study.

Table 1 Synopsis of main features of the papers in this special issue

Authors	Transportation/ economic system	Country	Spatial scale	Spatial/economic variables	Time period	Methodology	Vulnerability/ resilience	Approach
Modica and Reggiani	Spatial Economic	Various	Various	Various	2000–2014	Various	Resilience	Ecological and Engineering
O'Kelly	Transportation	U.S.A.	Regional/ National	Internet traffic, airline commuters, freight shipping	2002–2013	Network Analysis	Vulnerability	Disruption analysis
Jonkeren, Demeanu and Giannopoulos	Economic	Italy	National	Energy networks, transport networks	2003	Systems Engineering model and Input–output model	Resilience	Ecological and Engineering
Kuroda	Economic	–	National/ International	Goods' price, transport cost, supply chain (firm locations)	–	Supply–demand model	Resilience	Engineering
Ricottilli, Nardini and Andergassen	Economic	–	National/ International	Firms' technological capability	–	Evolutionary network dynamics	Resilience	Ecological
Caschili, Medda and Wilson	Transportation/ Economic	Worldwide	International	Trade, migration, cultural ties, economic ties	2000–2010	Multilayer Spatial Interaction Model	Resilience	Ecological
Griffith and Chun	Transportation	U.S.A., Germany and Puerto Rico	Urban/Regional	Commuters	2000–2002	Spatial Autocorrelation	Resilience and Vulnerability	Engineering
Connors and Watling	Transportation	–	Urban/Regional	Traffic flows	–	Traffic Equilibrium Model	Vulnerability	Ecological
Rupi, Bernardi, Danesi and Rossi	Transportation	Italy	Urban/Regional	Traffic flows	2013	Network Analysis	Vulnerability	Disruption Analysis

- *Vulnerability/Resilience* indicates if the study focuses either on resilience or vulnerability.
- *Approach* considers whether the study uses an approach to study resilience/ vulnerability from an engineering point of view (return to equilibrium after a shock), ecological approach (reach new equilibrium after shock), and/or disruption analysis (sensitivity of a system to shocks).

The first two papers set the groundwork for this SI, with their theoretical discussions on concepts and case studies linked to resilience and vulnerability of spatial economic and transportation networks. Starting from the basic definitions of resilience, Modica and Reggiani explore similarities and differences among the various definitions and applications of resilience in the spatial economics literature. O'Kelly draws together specific results and facts relevant to a variety of networks (cyber and air) in the context of vulnerability of hub interconnection points. Papers by Jonkeren et al. Kuroda, Ricottilli et al. and Caschili et al. present various models applied to case studies on Spatial Economic networks, while papers by Griffith and Chun, Connors and Watling, and Rupi et al. focus on case studies applied to transportation networks.

Table 1 shows that the authors use different approaches in their studies of resilience and vulnerability - which can be tied-in with the engineering view (Pimm 1984), ecological approach (Holling 1973) and disruption analysis (Sullivan et al. 2009). The engineering approach studies a system in its stable equilibrium and evaluates its ability to return to a stable equilibrium after a shock. Whereas in the ecological approach, a system is considered adaptive in the sense that it can evolve from a stable domain to another after being hit by a shock. Third, disruption analysis is a study of the sensitivity of a system in which shock(s) will compromise that system's functionality.

In summary, the papers included in this SI represent several of the current approaches used by scholars and practitioners in scrutinising resilience and vulnerability of spatial economic networks.

Modica and Reggiani review various contributions on resilience from the spatial economic literature. Spatial economic resilience appears to be a multifaceted concept, linked to the notions of stability (engineering resilience), but also to the idea of adaptation which is based on evolutionary theories (ecological resilience). The analysis and measurement of spatial economic resilience is related to specific shocks, specific contexts, aims, and the framework and spatial level adopted. However, the authors point out that only a few studies investigate resilience in depth from the theoretical viewpoint, while most studies investigate resilience empirically, using a variety of indicators and methods.

O'Kelly shows that air passenger, air freight, and other transportation/ communication systems have strong features drawn from complex scale free networks. There remains a question, however, whether a scale free power law provides any real process explanation for nodes (the hubs) with high degree. In short, the network may provide both the target and the solution to the problem of security/vulnerability. As long as there are alternative paths to work around a disruption, failure, or compromised link, the network can continue to operate.

Jonkeren et al. study the resilience of infrastructures and economic sectors in terms of their ability to withstand and recover from disruptions. They use the case study of the electricity blackout in Italy in 2003 to estimate the economic loss created by that

disruptive event. They adopt the definition of resilience given by Rose (2007, 2009), where both engineering and ecological approaches are taken into consideration as static and dynamic resilience.

Kuroda analyses the characteristics of supply chains over space in addition to the cascade of spatial risks. In this work although dynamic resilience is acknowledged, the author focuses on static resilience as a measure of the capability of supply chain producers to change the procurement pattern of intermediate goods in order to maintain levels of output as before (stable equilibrium).

Ricottilli et al. study the resilience of an evolving network of rationality-bounded firms engaged in the active search to improve their technological capability through interaction with knowledge-heterogeneous neighbours. Resilience is considered in terms of the system's ability to recover its innovative performance (after a shock) and reach (new) equilibria.

Caschili et al. apply an Interdependent Multilayer Model to study the interaction among economies by considering economic networks (trade, GDP, exchange rate), cultural networks (colonial and language ties) and spatial networks (transport). The model is used to evaluate the impacts of economic cascading effects at national and global scales. They adopt an ecological approach to study the resilience of international economic systems as the Multilayer model converges to a (new) equilibrium after a shock.

Griffith and Chun address the notion of spatial autocorrelation in the geographic distribution of origin and destination flows and illustrate that a spatial interaction model provides sound implications for associated economic network resilience and vulnerability. Resilience is considered from an engineering point of view. The authors study how quickly a journey-to-work system returns to an equilibrium after it experiences a perturbation.

Connors and Watling study the vulnerability of traffic networks by means of Stochastic User Equilibrium models. In particular, the authors evaluate the vulnerability of road networks when demand grows and affects traffic performance.

Rupi et al. scrutinise road network vulnerability and propose an interesting case study applied to the road network of the Province of Bolzano, a highly mountainous area in the Italian Alps. The authors investigate vulnerability of road networks by proposing an index which measures the consequences of a link disruption.

All in all, the different approaches and perspectives on resilience and vulnerability – presented in this SI – show the potential and promising aspects of these two complementary research areas, aiming to capture the contradictions and complexities of our networked space-economy (in the presence of positive/negative shocks), also in the light of new and adaptive policy strategies.

However, the diversity of the various approaches, here examined, highlights a clear need for additional research in this field. A first direction would be a strong research endeavour from the theoretical viewpoint, for example, by analytically linking non-linear dynamics and chaos/catastrophe theory, as well as complexity/network theory and economic theory, to resilience and vulnerability. Methodologically, a path towards the design of a unifying framework of these two concepts, to be tested in practice, would be desirable. Empirically, comparative studies of different vulnerability and resilience indicators – at different spatial scale levels (urban, regional, national, etc.)

– would give insight on which resilience/vulnerability approach would be appropriate for a specific spatial economic analysis.

References

Guha-Sapir D, Hoyois P, Below R (2013) Annual disaster statistical review 2012, WHO-CRED, Universite Catholique de Louvain

Holling CS (1973) Resilience and stability of ecological systems. Annual Reviews Ecological System 4:1–23

Miller FH, Osbahr E, Boyd F, Thomalla S, Bharwani G, Ziervogel B, Walker J, Birkmann S, van der Leeuw S, Rockström J (2010) Resilience and vulnerability: complementary or conflicting concepts. Ecol Soc 15(3): 11, Retrieved from: http://www.ecologyandsociety.org/vol15/iss3/art11/

Nijkamp P, Ratajczak W (2013) The spatial economy – a holistic perspective. FEWEB Research Memorandum 37. Retrieved from: http://dare.ubvu.vu.nl/bitstream/handle/1871/50705/2013-37.pdf?sequence=1

Pimm SL (1984) The complexity and stability of ecosystems. Nature 307:321–326

Reggiani A, De Graaff T, Nijkamp P (2002) Resilience: an evolutionary approach to spatial economic systems. Networks and Spatial Economics 2:211–229

Rose AZ (2007) Economic resilience to natural and man-made disasters: multidisciplinary origins and contextual dimensions. Environmental Hazards 7:383–398

Rose AZ (2009) A framework for analyzing the total economic impacts of terrorist attacks and natural disasters. Journal of Homeland Security and Emergency Management 6(1), art. 9

Seeliger L, Turok I (2013) Towards sustainable cities: extending resilience with insights from vulnerability and transition theory. Sustainability 5:2108–2128

Sullivan J, Aultman-Hall L, Novak D (2009) A review of current practice in network disruption analysis and an assessment of the ability to account for isolating links in transportation networks. Transportation Letters 1(4):271–280