Vulnerability, Resilience and Complex Structures: A Connectivity Perspective

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Disruptions such as natural disasters, pandemics, and wars may originate locally but spread widely, affecting material and social interdependencies far apart from the places that were first affected.

The propagation of disruptions takes place through channels provided by explicit or hidden connectivity between countries, regions, productive sectors, and socioeconomic groups. Connectivity patterns are of critical importance to the propagation of disruptions within the web of interdependencies connecting actors and processes. Disruptions work themselves out through networks of connectivity and bring about outcomes that cannot be satisfactorily explained by a simple shock-reaction pattern involving the elementary components of the system under consideration and the direct (i.e., first-level) connections between them. The propagation of disturbances within a web of connections brings to light typical features of complex system dynamics, in which 'a large number of parts […] interact in a nonsimple way', so that 'the whole is more than the sum of the parts, not in an ultimate, metaphysical sense but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole' (Simon 1962, p. 468). In other words, connectivity generates complex *structures,* whose architecture channels dynamic impulses along multiple layers of interdependence eventually delivering systemic outcomes.

Complex network structures are fundamental in determining the system's reaction to disturbances and the further evolution of linkages. In this connection, Albert-Laszlo Barabási pointed out that 'a thorough understanding of complex systems requires an understanding of network dynamics as well as network topology and architecture' (Barabási 2007, p. 34). As a result, 'complexity theory must incorporate the interactions between dynamics and structures' (Barabási, 2007 p. 34). Indeed, 'structural network theory is […] an unavoidable step toward the ultimate goal of understanding complex systems' (Barabási 2007, p. 41).

Disruptions bring to light the vulnerability to shocks of the affected system and the degree of resilience which that system may show in its response to it. The aim of this special issue is to provide the building blocks of a vulnerability-resilience heuristic that highlights connectivity as the central condition governing the propagation of disturbances and the activation of resilience. The formation of hierarchies is a characteristic feature of complex networks whenever different patterns of connectivity between network elements are associated with differences in the strength of linkages between elements. As Herbert Simon notes, the coexistence of strong and weak linkages introduces the decomposition of a complex structure into different subsystems, and the order of magnitude of interactions within each subsystem is generally different from the order of magnitude of interactions between different subsystems (Simon 1962, pp. 473-474). The *weight of connections* is thus a central feature of complex structures. This means that in a complex network in which linkages are strong within each subsystem but weak across different subsystems, dynamic impulses propagate within the overall network according to a particular 'order of motion' (Myrdal 1939; Landesmann and Scazzieri 1990; Scazzieri 2021) by which low-level networks (which link individual elements) are more likely to be immediately responsive to a disturbance – if directly affected by it – as compared to high-level networks (which link subsystems rather than individual network elements). As a result, the architecture of connectivity within a complex network structure generates a hierarchy of motions, which in turn makes certain patterns of connectivity more resilient than others. Simon introduced the concept of 'intermediate stable forms' as a condition for the resilience of complex structures (Simon 1962, pp.470-471). Our argument suggests that the emergence of intermediate stable forms may be associated with the emergence of a *hierarchic structure of connectivity*, and that features of resilience may be found at the intermediate levels of aggregation of the network under consideration. In this special issue, the papers by Donaghy (2022) ('A Circular Economy Model of Economic Growth with Circular and Cumulative Causation and Trade'*)*; Lichter, Friesz, Griffin and Bagherzadeh (2022) ('Collaborative Network Topologies in Spatial Economies'*)*; Reggiani (2022) ('The Architecture of Connectivity: A Key to Network Vulnerability, Complexity and Resilience'); and Scazzieri (2022) ('Decomposability and Relative Invariance: The Structural Approach to Network Complexity and Resilience') investigate features of complexity architectures centered upon the mutual influence of topology and connectivity in space and trade, the working of cumulative causation in networks, and the role of asymmetries and invariances within networks as key to network vulnerability and resilience.

The architecture of connectivity provides the channels along which a disturbance makes itself felt within a complex network structure. In particular, the internal hierarchy of a network makes certain connections more persistent than others and generates combinations of flexible and persistent linkages within the network. This means that certain connections may change more rapidly than others, and this generates the order of motions by which a complex network reacts to a dynamic impulse. As a result, a complex network will be more, or less, vulnerable to a shock depending on the *distribution of intermediate stable forms* within the internal hierarchy of the network. In general, a short hierarchy consisting of only few levels makes a network structure more vulnerable than a 'deep' hierarchy organized across many levels. This is because the latter may provide a 'cascade' of intermediate stable forms generating a nested architecture in which vulnerable connections could find a degree of protection in relatively invariant connections situated at a higher level of the hierarchy. In this special issue, the papers by R. Cardinale (2022) ('State-Owned Enterprises' Reforms and their Implications for the Resilience and Vulnerability of the Chinese Economy: Evidence from the Banking, Energy and Telecom'*);* Matisziw, Ritchey and MacKenzie (2022) ('Change of Scene: The Geographic Dynamics of Resilience to Vehicular Accidents'*);* Antonioli, Marzucchi and Modica (2022) **('**Resilience, Performance and Strategies in Firms' Reactions to the Direct and Indirect Effects of a Natural Disaster'*);* and Wirkierman, Bianchi and Torriero (2022) ('Leontief Meets Markov: Sectoral Vulnerabilities Through Circular Connectivity') discuss empirical cases of micro and macro shocks and of their propagation within connectivity structures that channel perturbations by governing the interplay between vulnerability and resilience.

Architectures of connectivity are central to the vulnerability and resilience of a complex network. However, a given network may be host to different patterns of connectivity, *which may become active, or recede into latency*, depending on actors' dispositions, objectives, and contexts of action. An example is provided by producers' networks, which may often give rise both to circular connections of processes feeding intermediate inputs into one another (Leontief 1991 [1928], 1941) and to vertical connections between processes sequentially related to one another along supply chains from primary resources to final products (Pasinetti 1973). In general, features of vulnerability and resilience will be different depending on which patterns of connectivity are active (Cardinale and Scazzieri 2019). This means that policies aimed at reducing vulnerability and increasing resilience require consideration of which pattern of connectivity is most significant, which may be different depending on the context and on actors' dispositions and objectives. In this issue, the papers by Borsekova**,** Koróny and Nijkamp (2022) ('In Search of Concerted Strategies for Competitive and Resilient Regions'); I. Cardinale (2022) ('Vulnerability, Resilience and "Systemic Interest" : a Connectivity Approach'); Cheng, Mi, Coffman, Meng, Liu and Chang (2022) ('The Role of Bike Sharing in Promoting Transport Resilience'); and Pereira and Steenge (2022) ('Vulnerability and Resilience in the Caribbean Island States; the Role of Connectivity') investigate resilience policies in a connectivity framework, the relationship between competitiveness and resilience, and the connectivity conditions for the emergence of constellations of interests compatible with effective policy design.

The central message of this special issue is that connectivity provides the unifying framework for the analysis of vulnerability and resilience. On this approach, different network architectures make complex structures differently vulnerable to shocks, alternative modes of connectivity entail different conditions for resilience, and successful resilience policies require actions compatible with the prevailing weight of connections in each context. Interdisciplinary research is a prerequisite for further advancing the analysis of vulnerability and resilience in complex network structures (Wilson 2022).

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