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RESEARCH

The Vulnerability-Redundancy Nexus through Connectivity. An Analytical Framework

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Abstract
The article proposes a new theoretical framework based on the conception of organized complexity and aims at linking fundamental dynamic properties of socio-economic systems to their architecture of connectivity. It emphasizes the role of stable intermediate forms and near-decomposability as the key to understanding vulnerability and resilience. The proposed approach provides a theoretical foundation for the role of redundancy as a condition lowering specific vulnerabilities, thus contributing – under certain conditions - to enhancing a system's resilience. The framework suggests that, while at intermediate levels of connectivity, increasing redundancy helps mitigate vulnerability, beyond a certain threshold, redundancy is usually associated with a return to rising vulnerability (vulnerability-redundancy paradox). The paper concludes by offering insights into policymakers to design interventions able to manage the trade-offs between vulnerability and efficiency

Keywords Vulnerability · Redundancy · Resilience · Connectivity · Organized complexity · Near-decomposable systems

1 Introduction

Over the past two decades, socio-economic systems have faced increasing stress from recurrent shocks, including financial crises, natural disasters, geopolitical changes, and global critical events like the COVID-19 pandemic. This has underscored the importance of strengthening the resilience of socio-economic networks. While empirical studies in economics and regional science have focused on the specific factors and structural characteristics that enhance resilience there is a growing

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need for a comprehensive theoretical framework to better understand the underlying mechanisms behind the dynamics of resilience in complex adaptive systems.

In this respect, Reggiani (2022) advocates that, on the theoretical ground, there is a need to advance in terms of a new general framework to guide empirical investigations, especially regarding some fundamental characteristics of complex systems such as connectivity and vulnerability. Sharing this viewpoint, the article proposes a new theoretical framework based on *organized complexity* (Weaver 1948). This starting point suggests a multilayered view of connectivity, in which the architecture of connectivity (Reggiani 2022) is systematically related to the architecture of complexity (Simon 1962) and the literature on relative structural invariances in structural dynamics (Landesmann and Scazzieri 1990, 1996; Scazzieri 2021). From this perspective, the article emphasizes the central role of stable intermediate forms and near decomposability as key to understanding vulnerability and resilience and informing policy makers.

More specifically, this work considers the relationship between redundancy and vulnerability to properly understand how to overcome shocks and manage possible trade-offs in complex networks. On one side, redundancy- additional elements or connections replicating a part of the system -improves the overall resilience or lower specific vulnerabilities as far as the system is near-decomposable, in line with the view put forward by Simon (1962). On the other side, increasing redundancy implies incurring in additional sunk costs, i.e., the fixed costs that are necessary to build back-up structures, elements or nodes. Thus, the architecture of connectivity can be interpreted as an expression of a system's resilience, it can be linked to its vulnerability to shocks as well as its efficiency[1], as will be presented in the model of Section 3.

Among the main conclusions, the framework proposed in this work identifies a possible trade-off between the dynamics of vulnerability and inefficiency under certain circumstances. Moreover, a vulnerability-redundancy paradox arises at high level of networks' connectivity. While at intermediate levels of connectivity, increasing redundancy helps mitigate vulnerability, above a certain threshold, further redundancy will start going hand in hand with growing vulnerability.

The article is organized as follows. Section 2 introduces the basic concepts that will be used throughout the paper, focusing on the central role of connectivity and redundancy in understanding organized complexity. Section 3 introduces the model to interpret the general dynamics of complex systems. Section 4 discusses how the model can be helpful to derive policy implications and offers some basic insights for a research agenda.

[1] In the course of the work, we assume that vulnerability is a concept referring to each state of the system, or sub-system, and its susceptibility to specific shocks. Instead, we conceive resilience as a higher property associated with the whole network.

Table 1 Definitions and main characteristics of vulnerability as a property of complex systems in human geography and evolutionary economic geography

Definition	References
Vulnerability is closely linked to resilience and can be defined as the extent or degree of susceptibility of a (socioeconomic) system as a whole or of any of its components to suffer damage or loss in the presence of adverse events, negative impulses, disruptions, or harmful external pressures	Adger (2000, 2006), Seeliger and Turok (2013), Reggiani et al. (2015)
Vulnerability and resilience of a local system are considered as separate but strictly related concepts. Vulnerability depends on endogenous structural characteristics of the local system, i.e., the organization and spatial ordering of the system components	Foster (2007), Boschma (2015), Bailey and Turok (2016); Graziano and Rizzi (2016, 2020); Reggiani et al. (2015); Reggiani (2022)
Vulnerability is a pre-shock characteristic of a social-ecological system, i.e., the propensity to suffer damage linked to resilience and adaptation.	Adger (2000) Cutter et al. (2008); Foster (2007); Pendall et al. (2012); Rose (2007); Martin and Sunley (2015)

2 Conceptual Framing

Before focusing on the proposed theoretical framework, it is important to outline the original definitions of the concepts under consideration, namely vulnerability, resilience, connectivity, and redundancy.

2.1 Vulnerability

Vulnerability, a key concept for understanding the dynamics of complex systems, can be defined as the extent to which a system or its components can be harmed by adverse events or external pressures. This concept includes both exogenous factors, like external shocks, and endogenous factors, such as the internal structural organization and connectivity of the system. Definitions of vulnerability in complex adaptive systems can be informed by insights from related fields, such as human geography and evolutionary economic geography (Table 1).

Concerning the relationship between resilience and vulnerability, it is possible to highlight different perspectives among scholars. Some scholars view resilience and vulnerability as strictly interconnected properties, with resilience being a positive trait and vulnerability linked to negative impacts (Reggiani et al. 2015; Seelinger and Turok, 2013) [2].

[2] The positive connotation of resilience is related to the possibility of opening new windows of opportunities to change in the systems that were even not conceived before the shock (Reggiani et al. 2015). Similarly, Scazzieri (2022) refers to the possibility for a network element of moving to another position within the range of possible transformations, the "buffer zone", a set of feasible paths that still allows to maintain over time the set of core interdependences that are typical of the system under analysis.

In fields like human geography and evolutionary economic geography, resilience is seen as a post-shock feature while vulnerability is viewed as a pre-shock characteristic (Adger 2000; Cutter et al. 2008; Foster 2007; Pendall et al. 2012; Rose 2007; Martin and Sunley 2015). According to Adger (2006), vulnerability may be viewed as the pre-shock susceptibility to damage and marginality, while resilience refers to a system's ability to recover from shocks and involves self-organization properties. In this perspective, the domains of vulnerability and resilience are connected through the adaptive capacity of the social-ecological system. Scazzieri (2022) further elaborates on this distinction suggesting that vulnerability might not go hand in hand with resilience, with vulnerable networks that can be resilient, and vice versa, even if the two characteristics are interconnected in practice and which one is more relevant depends on the contingency of time horizon and/or hierarchical level one is considering in the analysis (Scazzieri 2022).

Key factors in understanding network vulnerability include the connectivity architecture between nodes, the strength of ties, and the structural hierarchies within the system. Different socio-economic systems respond differently to shocks based on these structural configurations (Reggiani et al. 2015; Cardinale et al. 2022; Reggiani 2022; Simon 1962; Scazzieri 2022). In this respect, a proper design of network structure can allow to counteract networks' vulnerability and friability (Reggiani 2022). The latter is a concept closely related to vulnerability, where specific critical nodes or edges are essential for network stability and the whole functioning of a complex system since their removal may destabilize or even dismantle the entire network (Reggiani et al. 2015).

From the same perspective, the vulnerability concept adopted in this study emphasizes the central role played by the organization of the system components, the configuration of the network or networks that compose them, in other words, the architecture of connectivity (Reggiani 2021, 2022). Hence, in complex systems, we consider that the notions of vulnerability and resilience are separate but intertwined through the interacting connectivity structure.

2.2 Resilience

Resilience is defined as the ability of an individual, system, or community to absorb, adapt and recover from shocks, maintaining essential functions and structures. Originating in ecological studies, the concept has different meanings in various fields, such as psychology, engineering, disaster risk management, and economics.

Table 2 summarizes the main definitions of resilience in different disciplines.

In ecology, the concept of resilience was introduced by Holling in 1973 as an alternative to stability (Holling 1973). Thereinafter, it was further elaborated emphasizing the adaptation and transformative potential of dynamic systems (e.g., Folke et al. 2002, 2010; Gallopín 2006; Walker et al. 2004). In the engineering field, resilience takes on connotations that vary depending on the field of application, but all tend to revolve around resistance and recovery of structures in the face of external stresses (Ouyang 2014; Hosseini et al. 2016).

In psychology, the term indicates the ability of an individual to face adverse events and maintain a psychological balance (Rutter 1987; Werner 1995), influenced by

Table 2 Main definitions of resilience in different disciplines

Discipline/Field	Definition	References
Biology/Ecological studies	The ability of ecological systems to: (1) absorb changes of state variables, driving variables, and parameters, and still persist; (2) respond to a disturbance by reorganizing itself, that is, modifying its structure, despite the relative persistence of the relationships among sub-systems	Holling (1973), Walker et al. (2004), Folke et al. (2010)
Psychology	Individual's ability to: (1) "bounce back" or recover after adverse experiences. In this respect, protective variables that can play a key role in promoting resilience, are self-esteem, problem-solving aptitude, and social support networks	Rutter (1987)
	(2) face and overcome adversity, trauma, or stress, maintaining, or recovering a psychological balance	Werner (1995)
	(3) develop coping mechanisms and adaptive strategies, starting from childhood, which can be modulated by a series of factors, primarily the reference social networks: family environment, school experiences and interactions with peers	Cicchetti (2010)
	Positive adaptation to significant challenges	Luthar (2015)
Disaster risk management	The ability of a community or social network to resist and recover from adverse events, such as natural disasters or economic crises. This type of resilience, often referred to as "community resilience", emphasizes the importance of social cohesion, collaboration, and mutual support in promoting resilience in the face of adversity	Norris et al. (2008)
	Ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities that minimize social disruption and mitigate the effects of future earthquakes	Bruneau et al. (2003)
Engineering	In structural engineering, resilience represents the ability of any building or construction to resist external loads, such as strong winds or earthquakes, and to return to its original shape once the load has ceased. This definition emphasizes the need to design structures that are not only able to withstand such stresses but also to recover quickly to minimize damage and ensure safety. In electrical engineering, resilience is often associated with the stability and ability of electrical networks to respond to disturbances, such as faults or load changes, maintaining energy supply and preventing blackouts (Ouyang 2014). The definition, in this case, highlights the network's ability to maintain a dynamic balance in response to unexpected changes	Ouyang (2014)
	In systems engineering, resilience can be understood as the ability of a system to adapt and recover from malfunctions, failures or external threats, ensuring an acceptable level of functioning	Hosseini et al. (2016)
Economics	The ability of an economy to resist financial shocks and recover quickly (macroeconomic level)	Krugman (1999)
	The ability of local and regional economies to adapt to external shocks, such as technological changes or the loss of key industries	Briguglio et al. (2014).
	The ability of an economic system to anticipate, prepare for, respond to, and adapt to changes, rather than simply resist, or recover from them	Martin (2012)

Table 2 (continued)

Discipline/Field	Definition	References
	Four stages in the study of urban and regional systems: (1) vulnerability, or the susceptibility to damage, a pre-existing characteristic to the shock, (2) resistance, interpretable as the degree of sensitivity to the disturbance, (3) reorientation, understood as the adaptability of the territory in response to the shock and finally (4) recovery, understood as the speed and the degree of recovery. This typology has helped clarify the diversity and complexity of economic responses to challenges	Martin and Sunley (2015)
	Two definitions of economic resilience: engineering resilience and ecological resilience	Modica and Reggiani (2015)
	Resilience is defined as the ability of a region (or a local system or a city) to self-organize through autopoiesis mechanisms and respond to or use the disturbing event as an opportunity for change and development	Foster (2007), Boschma (2015), Bailey and Turok (2016); Graziano and Rizzi (2016, 2020); Reggiani et al. (2015)

individual, relational, and environmental factors (e.g., Masten 2001; Cicchetti 2010; Luthar 2015). In disaster management, resilience is seen as a collective phenomenon, linked to social cohesion and mutual support (Bruneau et al. 2003; Norris et al. 2008).

In economics, the interest in the factors affecting resilience has been growing significantly in the past two decades, from studies on macroeconomic stability and the necessity of regulatory and institutional mechanisms to respond to financial crises and avoid deep recession (Krugman 1999), to the regional and urban level, where studies focus on adaptation and economic diversification of regional and urban systems (e.g., Martin 2012; Briguglio et al. 2014; Martin and Sunley 2015; and Modica and Reggiani 2015). Recent research has exploited micro-level data to identify the characteristics that can explain the probability of firm survival to shocks (e.g., Bartoloni et al. 2021; Landini et al. 2020).

To summarize, resilience in different disciplines involves the dynamic process of overcoming shocks, and the ability of systems to withstand disruptions and return to a stable state or adapt to new conditions, highlighting both resistance and recovery capabilities. Moreover, it is worth stressing that connectivity is a key aspect in understanding resilience even if often it is not explicitly considered in different contexts and fields of study.

2.3 The Central Role of Connectivity for Vulnerability and Resilience in Organized Complexity

Complex systems are not merely the sum of their parts since the interactions between subsystems produce emergent properties (Weaver 1948; Simon 1962). Specifically, organized complex systems are often hierarchical, comprising sub-systems that can be further decomposed into lower-order elements (nodes). Simon (1962) introduces the concept of quasi-decomposability, where interactions within a subsystem occur more frequently and strongly than those between subsystems. This relationship significantly influences the evolutionary dynamics, vulnerability, and resilience of the entire network. In quasi-decomposable systems, the short-term behaviour of subsystems tends to be independent, while long-term interactions shape the overall aggregate behaviour of the system. The hierarchical structure thus affects both the transmission of negative impulses– i.e., vulnerability- and the adaptive capacity of the system in the long run -i.e., resilience (Scazzieri 2021, 2022). Therefore, while vulnerability is mostly referred to as short-term dynamics, resilience can be considered a long-term feature of complex systems. Additionally, relative structural invariance suggests that resilience in a part, or some parts of the network helps maintain the overall system's stability (Landesmann and Scazzieri 1996).

Connectivity refers to the links between the elements of a complex system, with different types of connectivity yielding distinct vulnerabilities. Scazzieri (2022) identifies two interpretations of connectivity: topological (based on geographical proximity) and functional (based on relationships among distant elements, such as those in international supply chains). Consequently, systems can experience contagion effects through their connectivity channels, revealing that different types of interactions can significantly affect the system's vulnerability and resilience.

Connectivity is also an essential characteristic of spatial networks. In this context, connectivity refers to maintaining connections between two or more parts, facilitating the transmission of disturbances and thus influencing network vulnerability (Reggiani et al. 2015; Reggiani 2022). At the same time, artificially creating new nodes or altering connections can mitigate vulnerabilities in some parts of the network. To the extent that these changes engender an increase in network redundancy, the overall resilience of a system can be strengthened.

The architecture of connectivity can be examined through the number and organization of connections among nodes. From this perspective, two polar network configurations emerge: *random networks*, characterized by a Poissonian distribution with many nodes having similar connectivity; and *scale-free networks*, depicted by a power-law distribution where a few nodes (hubs) have many connections, while most have few. Hubs– i.e., the nodes with a high number of ties- in scale-free networks serve as catalysts that significantly influence overall network behaviour (Barabási 2007). More precisely, the presence or absence of hubs in the network and, consequently, the structure of the network determines the vulnerability of a system (Reggiani 2022). In this respect, Barabási (2017) pointed out that systems with internal hubs are not vulnerable to the random failure of a certain number of nodes - an event which instead makes a network with homogeneous connectivity distribution highly vulnerable - but rather they are vulnerable to specific attacks directed at aggregator nodes.

Critical vulnerabilities arise from the organizational structure of the network and the presence of hubs (Reggiani 2022); while *scale-free networks* are resistant to random failures, they are susceptible to targeted attacks on these critical nodes (Barabási 2007). Understanding a system's connectivity architecture is thus essential to assess its vulnerability to shock propagation, redundancy, and efficiency. As Reggiani (2022) emphasizes, economic policies must consider the design of complex systems, especially in mitigating vulnerabilities associated with hubs by creating redundant structures.

2.4 Redundancy, Vulnerability and Resilience in Near-Decomposable Systems

The engineering-based concept of resilience focuses on designing intrinsically resilient systems and infrastructures by incorporating principles from various engineering disciplines and systems theory (Park et al. 2013; Hollnagel et al. 2006). This approach highlights the significance of sociotechnical aspects, as engineering systems are often embedded in broader social, economic, and environmental contexts, making their integration crucial for creating sustainable and socially acceptable designs (Righi et al. 2015).

A key aspect of organized complexity is redundancy, a characteristic that allows a system to maintain stability despite disruptions. Quasi-decomposable hierarchical subsystems have a high degree of redundancy, i.e., the repetitiveness of common patterns in the overall system architecture, a characteristic that can help to simplify system descriptions (Simon 1962). Research across various fields demonstrates that redundancy underpins resilience in communities facing seismic events (Bruneau et al. 2003), in urban transportation systems (Gonçalves and Ribeiro 2020) and in network analysis (Burt 1995) (Table 3).

The concept of redundancy in the course of the work will be related to the architecture of complex systems in the engineering conception (Perrow 1999; Downer 2009; Aven 2011), which inevitably also maintains the simplifying property already identified by Simon (1962). In this context, elements in a network are deemed redundant if they serve as backups for one another, enhancing overall system resilience. More generally, a system will be more redundant the more redundant elements it has within it (Downer 2009). Similarly, excess capacity or plenty of intermediate inputs in vertically integrated sectors are additional examples of redundancy that can help economic systems facing supply chains' idiosyncratic shocks (Scazzieri 2022).

In this view, redundancy improves overall resilience or lowers specific vulnerabilities as far as the system is near-decomposable, in line with the view put forward by Simon (1962) (Scazzieri 2021). However, while redundancy reduces vulnerability, it may also lead to increased costs and efficiency losses (Reggiani 2022) and possible new vulnerabilities. Thus, balancing redundancy with efficiency is essential to maintain regular production while ensuring adaptability to disturbances (Chatterjee and Layton 2020).

The present study also establishes that a certain level of redundancy is necessary to improve resilience without tipping into "excess complexity", which can paradoxi-

Table 3 Main characteristics of redundancy in the different definitions of resilience

Discipline/Field	Definition	References
	The presence of additional elements or links/connections replicating a part of the system. In this sense, redundancy improves the overall resilience or lower specific vulnerabilities as far as the system is near-decomposable	Simon (1962)
Organizational studies	The ability of a system to self-organize, adjusting one's internal structures and processes depending on the external circumstances to face	Streeter (1992)
Engineering resilience	A characteristic referring to the presence of additional components, sub-systems, or processes -generally double those strictly necessary- that can replace those failed ones, ensuring continuity of operations	Perrow (1999), Downer (2009), Aven (2011)
Economics	Excess productive capacity of an economic system	Scazzieri (2022)

cally undermine efficiency. This perspective aligns with Reggiani's conceptual curve, indicating that as connectivity increases in a network, vulnerability first rises, peaks, and then declines with further connectivity—though excessive redundancy can cause vulnerability to rise again (Reggiani 2022).

Overall, this research underscores the importance of understanding and measuring redundancy to inform policymakers about the resilience of socioeconomic systems and the trade-off between redundancy and efficiency which becomes stringent only once a sufficiently high degree of complexity is reached. In other words, a certain amount of redundancy is required to improve resilience and reduce vulnerability when moving toward organized complexity in the lower and intermediate stages of the system. But with an excess of connectivity, a further increase in redundancy may turn out to be worthless and thus unnecessarily expensive. In these circumstances, the efficiency of the overall system inevitably starts to decline. It is worth reminding that, in the present work, efficiency is used in the economic sense of *technical efficiency* and *production efficiency* without any consideration of welfare implications as in the notion of *allocative efficiency* and *Pareto efficiency*[3].

[3] In economics, the term *efficiency* refers to the optimal use of resources to achieve the desired outcomes. It encompasses *technical efficiency*, i.e., maximizing output from inputs; *production efficiency*, i.e. minimizing costs for a given output; and *allocative efficiency*, i.e., ensuring resources are distributed to maximize community well-being. *Pareto efficiency* (also referred to as Pareto optimality) describes a situation where no further improvements to society's well-being can be achieved through a reallocation of resources, that is, it is not possible through reallocation to make at least one person better off without making someone else worse off. Finally, in several real-world applications, the term efficiency usually involves a pragmatic cost-benefit analysis, whereby a quantitative assessment of all the effects of an economic scenario is undertaken to determine whether, on balance, the positive effects outweigh the negative ones.

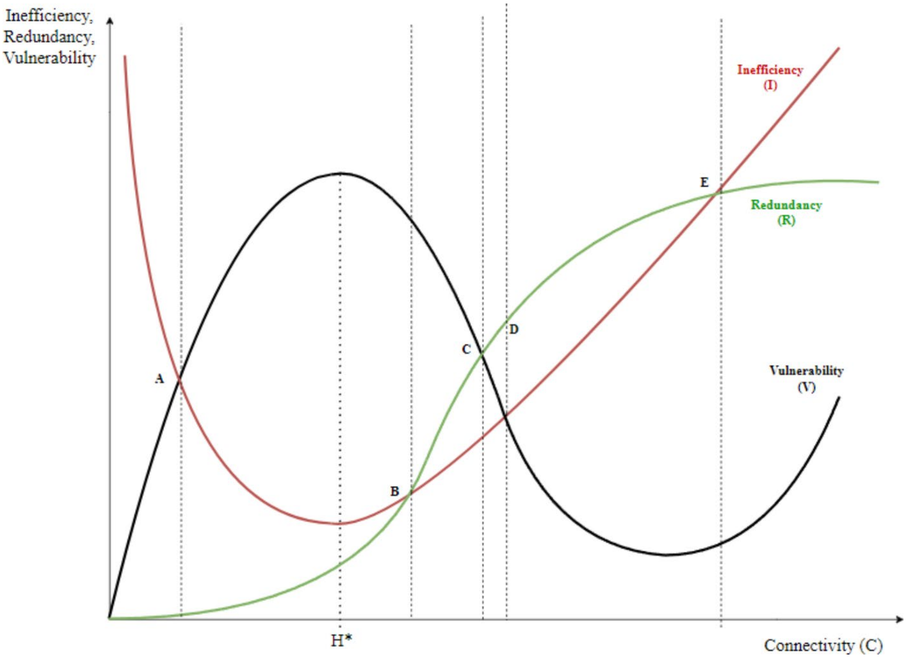

Fig. 1 Linkages between connectivity of a complex system with vulnerability, redundancy, and inefficiency

3 The Model

This section analyses the interaction between the fundamental properties of complex systems- in particular vulnerability and redundancy- and the connectivity architecture. A theoretical framework is presented in which the implications for cost minimization are discussed, as a corollary.

The model is based on three curves describing the dynamics of vulnerability, redundancy and inefficiency resulting from the architecture of connectivity: a vulnerability-connectivity relationship, a redundancy-connectivity relationship, and an inefficiency-connectivity relationship, as illustrated in Fig. 1.

We move from the analytical framework developed by Reggiani (2022) that highlighted how the architecture of connectivity is a key element in seeking an understanding of network vulnerability. We recall here that connectivity can refer to various topological characteristics, such as connection degree, centrality, and betweenness, usually adopted to describe complex spatial networks (Reggiani 2022). Since the present contribution is intended to provide a general view of economic systems, the connectivity index might also refer to additional properties of functional interdependence, i.e., the mutual response among sub-systems defining a hierarchy of motions (Scazzieri 2022).

Each complex system architecture of connectivity can be summarized by a connectivity index (H). At each stage of the evolution of a system, specific values for the three dimensions of Vulnerability (V), Redundancy (R), and Inefficiency (I) are associated with the degree of connectivity (H).

3.1 The N-shape Vulnerability-Connectivity Curve

The first curve, initially conceptualized by Reggiani (2022), illustrates that, as connectivity in a complex network increases, vulnerability initially rises, peaking at the creation of hubs (H*), then decreasing with further connectivity. However, excessive connectivity eventually causes vulnerability to rise again due to over-redundancy and interconnectedness among similarly vulnerable sub-systems and/or nodes. In the initial phase vulnerability increases because connectivity in the system is too low to guarantee mitigation of vulnerability. The hub creation (H*) corresponds to the maximum exposure of the whole system to vulnerability since the hubs are the most vulnerable nodes in the network in the absence of back-up nodes. Above point H*, intensifying connectivity can be a tool to enhance resilience through redundancy, as highlighted by Reggiani (2022). The curve describing vulnerability takes on an N-shape trend since for higher values of connectivity, the vulnerability would tend to rise again, due to an excessively enlarged network's dimensionality. In this case, unnecessary connectivity is associated with an excess of redundancy with noticeable implications in terms of growing inefficiency.

3.2 S-shaped Redundancy-Connectivity Curve

The second curve describes the evolution of redundancy as the system's connectivity increases. Adding redundancy, in this context, corresponds to artificially arranging a replication of a component or part of the system. In the absence of connectivity, redundancy is also zero. Redundancy first increases slowly and at the critical point H* associated with the onset of hubs in the system, redundancy will be positive but still insufficient to mitigate the high vulnerability of the early scale-free network. Then, redundancy displays an upward trend with increasing returns until a critical inflection point (B). In this phase, the increase in redundancy is also associated with a sharp reduction in vulnerability. However, for a higher level of connectivity, the curve becomes flatter as connectivity increases because of diminishing returns. It is worth noting that when the system is near-decomposable and all its sub-systems are backed up, then the minimum value of vulnerability is reached (near point E). After this point, adding further redundancy turns out to be inefficient due to increased costs that are not adequately balanced by the additional benefits, in terms of resilience.

Different phases can be identified according to the responsiveness of redundancy relative to an increase in connectivity in the different phases of the system. In detail, until nodes are isolated, that is, in the absence of connectivity, redundancy is zero. When the system has a low level of connectivity, that is when back-up nodes and connections are still too limited, an extra unit of connectivity leads to a small increase in redundancy. In this area, any additional piece of connectivity contributes to lowering vulnerability, but the architecture of the network is still insufficient to promote a sufficient degree of resilience. When the system has a sufficient level of complexity, near point B, a marginal increase in connectivity will lead to a large increase in redundancy. As the inflection point of the S curve is reached (point B), the substantial increase in redundancy is associated with a phase of growing resilience. In other words, between points B and C in Fig. 1 the system is characterized by network configurations with a degree of redundancy that greatly contributes to mitigating vulnerability. After point C the marginal contribution to redundancy per additional unit of connectivity slows down and, beyond a certain value of high connectivity (point E), it tends to become flat, settling redundancy at a constant and positive level. In this area, the influence of the n-th increase in connectivity will be irrelevant to the overall redundancy of the system since the latter will increase by an infinitesimal value. When a system ends up in this region, adding redundancy may even be negative from a resilience perspective, yielding to a complexity paradox: excess redundancy combined with increasing vulnerability (Downer 2009).

3.3 U-shaped Inefficiency-Connectivity Curve

The third curve describes the relationship between inefficiency and the architecture of connectivity.

The inefficiency curve (U-shape) indicates that at low levels of connectivity, inefficiency is high but decreases to a minimum at the creation of hubs (H*). Beyond point H*, inefficiency increases again, and the curve turns upward due to network fragmentation, particularly when excessive redundancy and inactive backup nodes contribute to system inefficiency, reflecting the vulnerability-redundancy paradox.

In detail, for low levels of connectivity, below point B, the network is highly inefficient. In this region, the nodes of poorly connected networks would fail to produce an adequate division of labour that is necessary to improve efficiency. As connectivity grows, the emergence of intermediate structures allows abandoning the “Smithian” area in favor of an area of organized complexity. The minimum level of inefficiency– maximum efficiency- coincides with the system configuration H* (hub creation) associated with a scale-free network, corresponding to a structure with nodes centralizing-aggregating tasks and resources in the system.

Beyond point H*, as connectivity increases, additional fragmentation among the network’s nodes, their tasks and resources may prompt increasing inefficiency leading to a “Byzantine” system architecture. Moreover, part of the rise of inefficiency will originate from the construction of back-up nodes (or hubs) of the network that remain idle in normal times and enter function when adverse impulses hit the system.

3.4 3.4 Interrelations Between the Curves: Relevant Areas

Exploring the interrelations between the three curves, Fig. 1 reveals that a low level of connectivity produces neither redundancy nor mitigates vulnerability, the latter peaks with the emergence of hubs. While networks composed of completely isolated nodes do not guarantee any benefit in terms of efficiency, reaching the scale-free structure (H*) allows the system to achieve maximum efficiency but also a higher degree of vulnerability.

On one hand, increasing redundancy could be helpful to mitigate vulnerability against different kinds of disruptions, first, shocks that specifically target hubs. In general, distributed redundancy improves complex system resilience (Randles et al. 2011). On the other hand, too much redundancy may produce even more complexity in the system. An excess of the number of parts in a network may lead to unexpected interactions that worsen the comprehensibility of the system. More importantly, excessive connectivity exposes the network to systemic risks, whose propagation, rather than being mitigated by redundant elements would be favoured by redundancy itself.

Figure 1 describes a system of interrelations where five areas can be identified, each area being delimited by the points of intersection between two of the three curves, by points A, B, C, D, and E. These areas can be classified into three distinct groups:

- ***Extreme areas: Areas between the origin and point A and beyond point E***.

These areas are polar cases: they have opposite characteristics, but both are harmful to every system. To the left of point A, where the curves describing the properties of vulnerability and inefficiency intersect, it is straightforward that the system is in an area with minimal connectivity and redundancy, thus exposing the system to increasing vulnerability as it approaches point A. The system is placed in a “non-Smithian” area where the absence of division of labor prevails, due to poor connectivity in the system. Similarly, the area beyond point E is characterized by increasing vulnerability, which is the result, in this case, of an excess of connectivity. Unlike the area below point A, the increase in vulnerability can mainly be attributed to the excessive complexity reached by the system due to unnecessary redundancy, well above the levels that would guarantee a satisfying degree of efficiency. Both areas are to be avoided as the system is exposed to serious structural weaknesses (either due to lack or excess of redundancy).

- ***Viable but unsatisfactory areas: between points A and B and between points D and E***.

Although these areas present trade-offs, they may be viable in certain contexts. In other words, these areas are not completely undesirable, but they require careful management to balance the trade-off between vulnerability and efficiency. The first region, the area between points A and B, is characterized by high vulnerability related to low redundancy but also high efficiency. In this area, the minimization of inefficiency is associated with the maximum peak corresponding to the emergence of the hubs (Reggiani 2022). This area can be viewed as a desirable phase in a development process, mainly due to the presence of H* which represents the transition from a random network to a scale-free architecture. However, from an evolutionary perspective, the process should not stop at H* since redundancy, almost absent up to point H*, begins to accelerate after the emergence of a free-scale architecture. The second region, the area between points D and E, is characterized by increasing redundancy that helps lower vulnerability to its minimum point, that is– in near-decomposable systems - when all its sub-systems are backed up. At this point, adding further redundancy turns out to be highly inefficient due to increased costs that are not adequately balanced by the additional benefits in terms of resilience.

- ***Satisfactory area***[4]: ***between points B and D***

This region is characterized by neither minimum nor maximum points. However, each connectivity level is associated with a combination of Vulnerability-Redundancy-Inefficiency that represents a satisfactory balance among the three fundamental properties of a system. Moving from point B to point D, vulnerability is steeply decreasing, redundancy is in an upward trend with marginal contributions that are still high, and the inefficiency curve, although increasing, is still close to its minimum value.

4 Discussion, Policy Implications, and Insights into a Research Agenda

4.1 Discussion and Policy Implications

The previous section conceptualizes the relationships among redundancy, vulnerability and inefficiency in complex systems, emphasizing how these properties interact based on the system's connectivity structure.

As already emphasized, it is assumed that policymakers like individuals are characterized by bounded rationality and therefore adopt a satisfying approach to decision-making (Simon 1955, 1969). Recognizing the dynamic and evolving nature of complex systems, the model highlights that there is no optimal point but rather a "satisfactory" range of possible states where a viable and contingent balance among these properties can be achieved. The policy implications derived from the proposed model revolve around managing the trade-offs between vulnerability and inefficiency in complex systems. Policymakers should avoid areas of low connectivity (before point A) characterized by lack of redundancy, high inefficiency, and rapidly growing vulnerability. Similarly, they should avoid the region beyond point E, where excessive connectivity results in unnecessary redundancy and rising inefficiency, which increases vulnerability again.

Hub creation, with its centralization of functions and resources and no redundancy, leads to the system's vulnerability being concentrated on the hubs. Beyond point H*, it becomes possible to introduce backup structures, thus enhancing system resilience. However, this comes at the cost of efficiency: adding redundant components intro-

[4] it is assumed that policymakers like individuals are characterized by bounded rationality and therefore adopt a satisfying approach to decision-making (Simon 1955, 1969). We draw from H. Simons's behavioural theory of decision-making processes by individuals and organizations with bounded rationality (Simon 1955). In The Science of Artificial Simon recalls that "*In the face of real-world complexity, the business firm turns to procedures that find good enough answers to questions whose best answers are unknowable. Because real-world optimization, with or without computers, is impossible, the real economic actor is in fact a satisficer, a person who accepts "good enough" alternatives, not because less is preferred to more but because there is no choice.*" (Simon 1969; pp. 28–29).

duces sunk costs due to the resources required for their creation and maintenance. From the policymaker's perspective, the main undesirable characteristic of these intermediate areas (A-B and D-E) is the inefficiency increase prompted by further redundancy into the system. At very high levels of connectivity, the benefits in terms of redundancy become negligible, and further increases in connectivity have detrimental effects not only on efficiency but also on resilience. In line with the theory of complex adaptive systems, the framework does not seek to identify a stasis or equilibrium point. Instead, it focuses on assessing the interactions between vulnerability, redundancy, and inefficiency to find a "satisfactory" mix appropriate for the system's contingent state and policy makers' preferences.

In terms of policy implications, the conceptual framework highlights the importance of considering the contingency on which the system is situated. While every policy maker, whatever priorities and preferences, will tend to keep the system away from the extreme areas (below A and above E) by increasing or decreasing the degree of connectivity, the intermediate areas (A-B and D-E) can be viable in specific contexts if trade-offs are managed strategically.

The real challenge for the policymakers will be positioning the system within the satisfactory area between B and D, which requires flexible and adaptive management. A policymaker highly committed to efficiency will prefer levels of system connectivity in the left frontier of the area, near point B, as close as possible to the local minimum of inefficiency. On the contrary, a policymaker more oriented towards the objective of resilience will try to drive the system near point D, corresponding to the local minimum of vulnerability and the local maximum of redundancy. While balancing the three key dimensions is possible, it is crucial to avoid a static perspective. The ability of a system to evolve, absorb external shocks, and adapt may require temporary deviations from this "satisfying area" toward more vulnerable or inefficient configurations to maximize other objectives (e.g., expansion). Ultimately, while Fig. 1 identifies desirable zones, policymaking should adopt a more comprehensive dynamic approach, accounting for the evolution of trade-offs over time, the nature of the system under consideration, and shifting priority objectives.

4.2 Concluding Remarks and Basic Insights into the Research Agenda

Our approach suggests new and powerful insights for treating the vulnerability-redundancy nexus both from the analytical point of view and the point of view of policy implications (discussed in Section 4.1). For example, implications that could be considered are those for scaling laws in the presence of structural network dynamics, and those for fractal structures in nearly decomposable systems in which different stable intermediate forms should withstand various types of shock.

Our framework, which considers the trade-off between vulnerability and inefficiency, represents a significant step toward understanding resilience in complex networks. It can be applied to any type of complex system and can address different real-world problems, such as the relationship between product complexity and market structure in terms of trade-off and issues of resilience and efficiency in the organization of both international supply chains and positional clusters.

The theoretical framework proposed in this work is useful for understanding the consequences of shocks in economic segments in which the underlying production process and the connected supply chain are geographically extended on a global scale. The COVID-19 pandemic and the spatio-temporal evolution of the health emergency around the world have highlighted the complexity and vulnerability of global supply chains, with supply and demand shocks that affected essential and non-essential industries in several parts of the world. Another example can be drawn from the organization of positional clusters, i.e., topological networks of production firms. Also, in this case, the concepts of relative structural invariance and connectivity are useful. Over the last three decades, the evolution of local systems has been increasingly affected by globalization and the emergence of global supply chains. Nowadays, most of the economic complexity is due to the intertwined dynamics of positional clusters and international production networks. In recent years, the most resilient clusters are those with a hierarchical quasi-decomposable structure where each subsystem denotes a production hierarchical network with a leader firm that represents the hub. The pivotal firm has an important role in relative structural invariance: its behavior and stability reverberate over the entire local production system throughout the various linkages with suppliers and producers of intermediate inputs on a local and global scale. In this context, the resilience of positional clusters can be achieved through maintaining relative independence[5] among the sub-systems internal to each cluster with a hub-and-spoke configuration. Over time, both global supply chains and topological networks have evolved towards quasi-hierarchical structures with medium-sized firms and global firms representing the hubs of both types of complex networks. A shock that hits an international production network could reverberate in a regional economy if the firms mostly involved are also a hub of a local production network.

Empirical research on networks, informed by this theoretical foundation, can help in identifying interactions and thresholds that require targeted policy responses to avoid undesired trajectories. However, the next essential steps should be taken on theoretical grounds to further progress towards a mathematical modelling approach. At this stage of formalization, the proposed approach focuses on identifying areas of trade-offs rather than one or more equilibrium solutions. Hence, we advocate that further research is essential to accurately describe the dynamic behavior of the system. The dynamic analysis to be conducted requires the formalization of the laws describing the model, the identification of equilibria and the study of their local stability. The qualitative structure of attractors may consist of fixed or periodic points or, even, chaotic sets. Hence, of particular interest is the investigation of bifurcations with respect to parameters of interest and of the basins of attraction in the case of multi-stability. Such questions can be explored both by assuming continuous or discrete time, i.e., using differential or difference equations.

In conclusion, the connectivity framework underlying vulnerability, redundancy and (in)efficiency should be intended as an intermediate though fundamental step

[5] For example, independence among different hierarchical sub-systems within a positional cluster can be achieved though maintaining different specialization of the different hubs so as to not be susceptible to similar shocks.

towards a more comprehensive analytical approach to understanding the dynamic behavior of socio-economic systems and their resilience.

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Declarations

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