The efficiency redundancy trade-off through connectivity. An analytical framework

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Introduction/Aim

The article intends to offer a new perspective to understand the linkages between redundancy, efficiency, and vulnerability in complex systems. Redundancy is here considered as one of the main drivers of resilience and vulnerability, a characteristic to which every system is exposed, while efficiency is often the main purpose in the organization of economic systems. Relationships will be identified between these characteristics and connected to the degree of connectivity of each complex system.

Among the main conclusions, the framework proposed in this work identifies a trade-off between redundancy and efficiency, above certain levels of connectivity, the hypothesis is that, above a certain threshold, an increase in redundancy will mitigate the vulnerability of the system.

This theoretical proposal aims to be the basis for a more extensive work to derive a general evaluation system to support policymakers in the resolution of critical issues in the organization of networks. Moreover, the framework could be used for the identification of the right mix of policies for the sustainable development of modern economic systems (and sub-systems) that are usually highly interconnected.

Conceptual framing

Before focusing our attention more directly on the proposed theoretical framework, based on a literature review, it is important to outline the original definitions of the two main concept under consideration.

Starting from the main notion of resilience in the literature - the engineering-based concept of resilience, the ecological concept of resilience and the evolutionary approach to resilience- the engineering notion of resilience is, to our purposes, of particular interest in that it focuses on the design of systems and infrastructures that are intrinsically resilient, integrating principles from various branches of engineering with approaches based on systems theory (Park et al., 2013). This multidisciplinary approach addresses resilience not only as an intrinsic characteristic but also as an objective of the system design itself.

A key aspect of resilience engineering is the holistic approach. This means that, in addition to focusing on individual components or aspects of a system, it is taken into consideration in its complexity (Hollnagel et al., 2006). For example, when designing a transport network, one not only considers the robustness of individual infrastructures, but also how they interact with each other and with the surrounding environment.

Research in this field has also highlighted the importance of considering sociotechnical aspects. Engineering systems are often embedded in broader social, economic, and environmental contexts. Ignoring these linkages can lead to suboptimal or even counterproductive solutions. The integration of sociotechnical principles into the design of resilient socioeconomic systems is therefore essential to ensure that they are not only robust, but also sustainable and socially acceptable (Righi et al., 2018).

Redundancy is among the key concepts in the engineering notion of resilience. It is particularly relevant when it comes to ensuring that systems remain active in the face of malfunctions or disruptions. In engineering terms, redundancy refers to the presence of additional components, systems or processes that can replace those failed ones, ensuring continuity of operations (Aven, 2011).

Streeter (1992) highlighted the conceptual proximity between resilience and redundancy. He defines redundancy as the ability of a system to self-organize, adjusting one's internal structures and processes depending on the external circumstances to face.

Redundancy is also considered by Herbert Simon in his seminal work "The Architecture of Complexity" (1962) as a crucial property for the descriptive purposes of a system. According to his view, most hierarchical systems, i.e. decomposable into composite subsystems, have a high degree of redundancy, expressed as the repetitiveness of common patterns in the architecture. According to Simon, this redundancy property is a central element in the possibility of simplifying the hierarchical description of the system itself.

The concept of redundancy in the course of the work will be related to the architecture of complex systems in the engineering sense, which inevitably also maintains the simplifying property already identified by Simon. An element of a network or system will be considered redundant if it turns out to be a back-up to another in performing the same function. More generally, a system will be more redundant the more redundant elements it has within it (Downer, 2009). From this perspective, the measurement of redundancy is aimed at providing policy makers with an understanding of the state of resilience of the system.

A crucial aspect of designing resilient socioeconomic systems is the definition of a balance between redundancy and efficiency. Adding redundancy can enhance the robustness of a system, but sometimes this happens at the expense of an efficient use of resources, implying increased costs and new vulnerabilities. Resilience engineering therefore seeks to find an optimal balance between redundancy and efficiency, considering the specific context and potential threats (Downer, 2009; Taleb, 2012). Designing and organizing a system with a certain degree of redundancy, given its hierarchical structure, may not always be a trivial operation and without drawbacks.

From such a perspective, the objective becomes to modify the structural architectures of our systems by rebalancing the relationship between redundancy and efficiency so as to be able to maintain production systems in normal circumstances and, at the same time, guarantee their ability to adapt and overcome the disturbances they have to face (Chatterjee and Layton, 2020).

As shown by the numerous fields of application, the ecosystem model that links together vulnerability, redundancy, efficiency, and resilience can find application in any type of complex system. Describing their interrelationships and dynamics is the purpose of this article.

Empirical evidences

Complex systems theory, as well as network theory, offer an extremely useful framework for understanding the actual functioning of organizational architectures in various fields, from technology to biology, from economics to ecology. There are numerous examples of how the organizational structures of the networks we experience in everyday life impact on the transmission of shocks, highlighting the vulnerability associated with the hierarchical structure of the network, in the presence of hubs, i.e. highly connected central nodes.

The transport sector, and particularly the aviation sector, is well suited to describing the possibility of contagion and the dynamic in the transmission of shocks. Not all airports offer the same number of destinations. This is a clear example of scale-free network where some, few, nodes have a very high number of connections. These nodes act as hubs and play a fundamental role in the efficiency and smoothness of global air traffic. Their ability to effectively manage a large volume of air traffic not only influences the punctuality of flights but also the efficiency of airlines and the travel experience of passengers. Airport hub congestion can have ripple effects on a global scale. A delay at a hub airport can cause delays in arriving and departing flights, affecting not only domestic routes but also international ones. This phenomenon emerges during extreme weather events. In addition to weather events, other factors can cause disruptions at airport hubs. Staff strikes, technical issues, or health emergencies, as seen during the COVID-19 pandemic, can dramatically reduce the operational capacity of main airports, resulting in large-scale delays and cancellations.

Resilience achieved through increased redundancy is also a crucial concept in this context, both for airport infrastructures and for airlines. You need to have contingency plans and alternative back-up routes. Some airlines have developed strategies to diversify their hubs or use secondary airports to reduce dependence on a single hub. This approach improves the resilience of the system as a whole by offering benefits in terms of reducing congestion, improving overall efficiency and more uniform distribution of risk throughout the network.

The role of hubs in social networks, both real and virtual, has become a topic of growing interest, particularly considering recent sociopolitical phenomena linked to the spread of information and disinformation. Hubs in social networks are crucial in shaping the information landscape. With their wide network of connections, they allow the rapid dissemination of information to a wide audience. This can have positive effects, such as the rapid dissemination of vital or educational information, but it can equally have negative implications, such as the dissemination of misleading or false information. The centrality of hubs in social networks therefore makes them vulnerable to misinformation.

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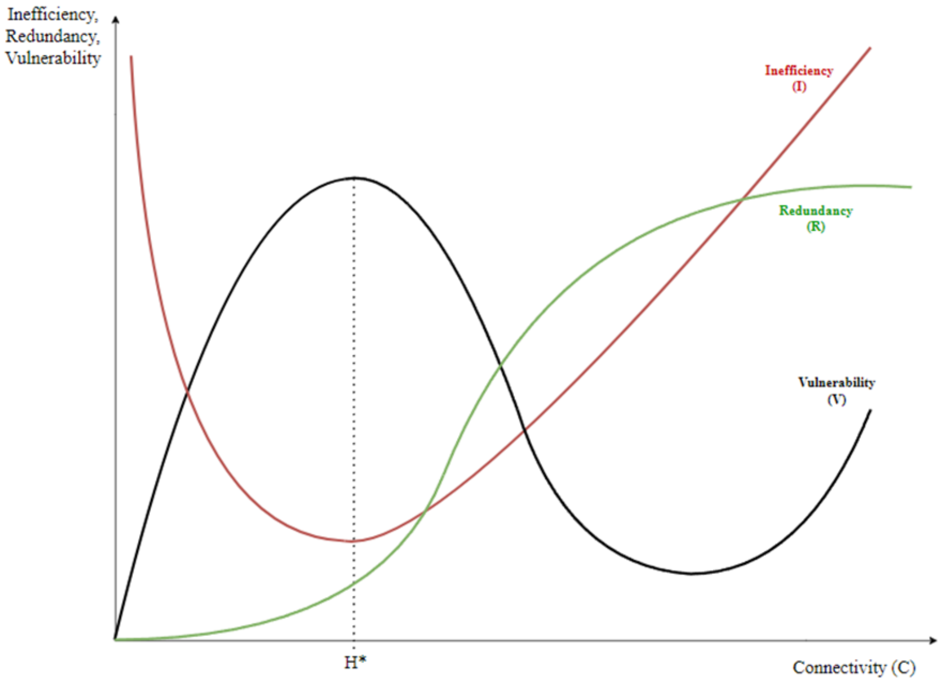
The model

Each complex system architecture of connectivity can be empirically linked to a measure, a connectivity index (H). At each stage, specific values for the three dimensions of Inefficiency (I), Redundancy (R), and Vulnerability (V) are associated to the degree of connectivity, to derive the overall resilience of a system.

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



This section aims to conceptualize the linkages between redundancy, efficiency and vulnerability in complex systems. Each connectivity architecture of a complex system can be summarized in a measure, such as a connectivity index (H), which, in each phase of the development and evolution of the system, corresponds to specific values for the three subdimensions of Inefficiency (I), Redundancy (R) and Vulnerability (V). These quantities, considered simultaneously, can help to highlight the degree of overall resilience of a system.

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Conclusions and policy implications

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