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A review of definitions and measures of system resilience

Seyedmohsen Hosseini [a], Kash Barker [a,*], Jose E. Ramirez-Marquez [b,c]

[a] School of Industrial and Systems Engineering, University of Oklahoma, United States
[b] School of Systems and Enterprises, Stevens Institute of Technology, United States
[c] Tec de Monterrey, School of Science and Engineering, Zapopan Guadalajara, Mexico

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A B S T R A C T

Modeling and evaluating the resilience of systems, potentially complex and large-scale in nature, has recently raised significant interest among both practitioners and researchers. This recent interest has resulted in several definitions of the concept of resilience and several approaches to measuring this concept, across several application domains. As such, this paper presents a review of recent research articles related to defining and quantifying resilience in various disciplines, with a focus on engineering systems. We provide a classification scheme to the approaches in the literature, focusing on qualitative and quantitative approaches and their subcategories. Addressed in this review are: an extensive coverage of the literature, an exploration of current gaps and challenges, and several directions for future research.

1. Introduction

Historically, the primary questions asked during a risk assessment study are: (i) what can go wrong?, (ii) what is the likelihood of such a disruptive scenario?, and (iii) what are the consequences of such a scenario? [1]. Risk management strategies have traditionally focused on reducing the likelihood of disruptive events and reducing the potential consequences of the event, as well as some synthesis of both. As such, risk management strategies often emphasized mitigation options in the form of prevention and protection: designing systems to avoid or absorb undesired events from occurring. The main objective of protection strategy is to detect the adversary early and defer the adversary long enough for an appropriate respond. While a protection strategy is critical to prevent undesired events or consequences, however recent events suggested that not all undesired events can be prevent. Hurricane Sandy, which devastated NY/NJ in 2012, is among the more recent examples of a disruptive event that adversely impacted multiple networked systems (e.g., months after the storm, power had not been restored to all communities in the NY/NJ area [2], one million cubic yards of debris impeded transportation networks [3]). Plenty of other disruptions have highlighted the resilience, or lack thereof, of networked systems: the August 2003 US blackout that caused transportation and economic network disruptions [4], Hurricane Isabel devastated the transportation system of the Hampton Roads, VA, region in 2003 and overwhelmed emergency response [5], the 2011 9.0 magnitude earthquake and tsunami that struck Japan, causing over 15,000 confirmed deaths and disrupting global supply chain networks [6]. It is because of these recent large-scale events that the Department of Homeland Security, among others, has placed emphasis on resilience through preparedness, response, and recovery [7,8].

The term *resilience* has increasingly been seen in the research literature [9] and popular science literature [10] due to its role in reducing the risks associated with the inevitable disruption of systems. This paper presents a comprehensive review of resilience in various disciplines, published from 2000 to April 2015. In this paper, we primarily focus on the quantitative perspective of modeling resilience, distinguishing our work from existing excellent review papers [11,12].

The word resilience has been originally originated from the Latin word “resiliere,” which means to “bounce back.” The common use of resilience word implies the ability of an entity or system to return to normal condition after the occurrence of an event that disrupts its state. Such a broad definition applies to such diverse fields as ecology, materials science, psychology, economics, and engineering. A graphical depiction of the initial impact and subsequent recovery of a six recent U.S. recessions is shown in Fig. 1 [13]. For example, figure shows that for the 1980s recession, there was a disruption that affected a change roughly equal to -1.2% and that the recovery lasted roughly six months.

Several definitions of resilience have been offered. Many are similar, though many overlap with a number of already existing concepts such as *robustness*, *fault-tolerance*, *flexibility*, *survivability*, and *agility*, among others.

* Correspondence to: School of Industrial and Systems Engineering, University of Oklahoma, 202W. Boyd St., Rm. 124, Norman, OK 73019, United States.
Tel.: +1 405 325 3721; fax: +1 405 325 7555.
E-mail address: kashbarker@ou.edu (K. Barker).

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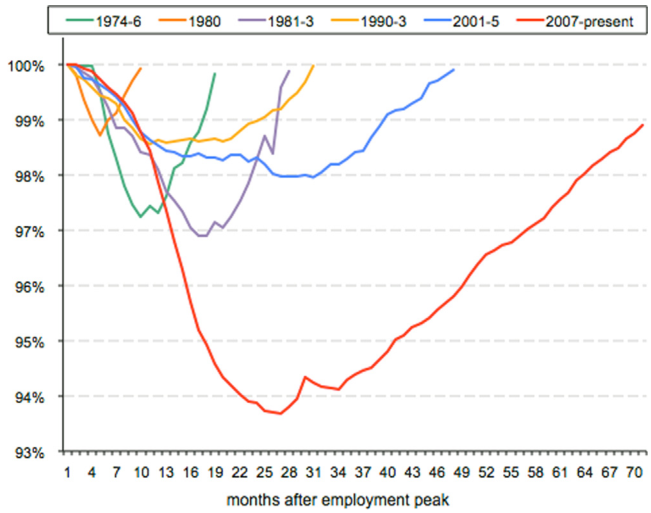

Fig. 1. Payroll change in recent recessions [13].

Some general definitions of resilience that span multiple disciplines have been offered. For example, Allenby and Fink [53] defined resilience as the "capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must." Pregenzer [54] defined resilience as the "measure of a system's ability to absorb continuous and unpredictable change and still maintain its vital functions." Haimes [55] defined the resilience as the "ability of system to withstand a major disruption within acceptable degradation parameters and to recover with a suitable time and reasonable costs and risks." Disaster resilience is characterized by Infrastructure Security Partnership [56] as the capability to prevent or protect against significant multi-hazard threats and incidents, including terrorist attacks, and to recover and reconstitute critical services with minimum devastation to public safety and health. Vugrin et al. [57] defined system resilience as: "Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is that system's ability to reduce efficiently both the magnitude and duration of deviation from targeted system performance levels." Two elements of this definition are noted: system impact, the negative impact that a disruption imposes to a system and measured by the difference between targeted and disrupted performance level of system, and total recovery efforts, the amount of resources expended to recover the disrupted system.

The concept of resilience has also been approached from particular disciplinary perspectives and across application domains, including psychology, ecology, and enterprises, among others. A variety of definitions for the notion of resilience have been proposed. We identify four domains of resilience: organizational, social, economic, engineering. Note that this classification may vary depending on researcher's perspective. We provide a variety of definitions of resilience according to the four aforementioned groups.

1.1. Organizational domain

The concept of organizational resilience has emerged to address the need for enterprises to respond to a rapidly changing business environments. The resilience of an organization is defined by Sheffi [19] as the inherent ability to keep or recover a steady state, thereby allowing it to continue normal operations after a disruptive event or in the presence of continuous stress. Vogus and Sutcliffe [20] defined organizational resilience as "the ability of an organization to absorb strain and improve functioning despite the presence of adversity." Sheffi [21] defined resilience for companies as "the company's ability to, and speed at which they can, return to their normal performance level (e.g., inventory, capacity, service rate) following by disruptive event." McDonald [22] defined resilience in the context of organizations as "the properties of being able to adapt to the requirements of the environment and being able to manage the environments variability." Patterson et al. [23] highlighted that collaborative cross-checking can greatly enhance the resilience of organizations. Collaborative cross-checking is an enhanced resilience strategy in which at least two groups or individuals with different viewpoints investigate the others' activations to evaluate accuracy or validity. By implementing collaborative cross-checking, erroneous actions can be detected quickly enough to mitigate adverse consequences. More definitions of resilience in the context of organizational, enterprises and can be found in [24–27].

1.2. Social domain

The social domain looks at the resilience capacities of individuals, groups, community, and environment. Adger [28] defined social resilience as "ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change." The Community and Regional Resilience Institute [29] defined the resilience as the capability to predict risk, restrict adverse consequences, and return rapidly through survival, adaptability, and growth in the face of turbulent changes. Keck and Sakdapolrak [30] defined social resilience as comprised of three dimensions: coping capacities, adaptive capacities, and transformative capacities. The term of community resilience is described by Cohen et al. [31] as ability of community to function properly during disruptions or crises. Pfefferbaum et al. [32] defined community resilience as "the ability of community members to take meaningful, deliberate, collective action to remedy the effect of a problem, including the ability to interpret the environment, intervene, and move on". The concept of resilience has been well studied in subdomains of the social domain such as ecology [33–35], psychology [36–38], sociology [39–42].

1.3. Economic domain

Rose and Liao [43] described economic resilience as the "inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses." Static economic resilience is referred by Rose [44] as the capability of an entity or system to continue its functionality like producing when faces with a severe shock, while dynamic economic is defined as the speed at which a system recovers from a severe shock to achieve a steady state. A more specific definition of economic resilience is presented by Martin [45] as "the capacity to reconfigure, that is adapt, its structure (firms, industries, technologies, institutions) so as to maintain an acceptable growth path in output, employment and wealth over time."

1.4. Engineering domain

The concept of resilience in the engineering domain is relatively new in comparison to other domains. The engineering domain includes technical systems designed by engineers that interact with humans and technology, such as electric power networks. Note that Youn et al. [14] defined engineering resilience as the sum of the passive survival rate (reliability) and proactive survival rate (restoration) of a system. Another definition of engineering resilience is presented by Hollnagel et al. [15] as the intrinsic ability of a system to adjust its functionality in the presence of a disturbance and unpredicted changes. Hollnagel and Prologue [16] pointed out that, for resilience engineering,