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Approaches for resilience and antifragility in collaborative business ecosystems

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ABSTRACT

Contemporary business ecosystems are continuously challenged by unexpected disruptive events, which are increasing in their frequency and effects. A critical question is why do some organizations collapse in face of extreme events, while others not? On the other hand, current engineering and socio-technical systems were designed to operate in "mostly stable" situations; sporadic instability and disturbances are at best captured by exception handling mechanisms, focusing on reliability and robustness. Recent and more ambitious design goals, however, aim at building systems that are expected to cope with severe disruptions, and survive or even thrive in a context of volatility and uncertainty. This led to an increasing attention to the concepts of resilience and antifragility. As such, this article introduces the findings of a comprehensive literature survey aimed at shedding light on emerging concepts and approaches to handle disruptions in business ecosystems. Main contributions include a clarification of related concepts, identification and classification of disruption sources and drivers, and extensive lists of strategies and underlying capabilities to cope with disruptions. Related perspectives and approaches developed in multiple knowledge areas are also analysed and synthesized. Finally, a collection of engineered systems implementing promising approaches to increase resilience and antifragility are presented.

1. Introduction

Contemporary societies and their organizational structures and systems are increasingly exposed to unexpected disruptive events (Pettit et al., 2013). Variability and randomness are the rule of our complex world and not the exception (Taleb, 2012) leading to large uncertainty, often caused by the accumulation of a number of factors, such as the climate change, economic crises, political instability, terrorism, changes in regulations, more dependency on technology, demographic shifts, and immigration (Chroust and Aumayr, 2017; Chroust et al., 2016).

The increase in frequency and impacts of disruptive events in recent years such as, for instance, the terrorist attack of 9/11, earthquake and resulting tsunami in Japan on March 2011, the hurricane Katrina, the SARS epidemic, and the Arab Spring, strongly affect the vulnerability of the global business environment (Murino et al., 2011; Faisal et al., 2006). Recent examples show that major supply chain disruptions can have severe impacts on industry, society, and economy (Carvalho et al., 2012; Bhamra et al., 2011). For instance, the 2011 earthquake and tsunami in Japan and the subsequent nuclear disaster caused an estimated economic damage from $195 billion to $305 billion (Pettit et al., 2013).

The effects and consequences of such extreme events are often unpredictable and harmful to many areas of business and have changed the concept of planning and readiness for disasters (Gotham and Campanella, 2010). Furthermore, it is plausible to foresee future scenarios in which turbulence and instability are no longer considered as an episodic crisis, rather the "norm" or the default status (Chroust and Aumayr, 2017).

At the same time, complex and competitive business environments encouraged companies to implement new business practices such as lean manufacturing in order to increase efficiency. Moreover, evolving from individual business models to new collaborative organizational forms such as extended supply chain networks and business ecosystems, has increased dependence on outsourcing and global partnerships. Although these aspects have made business operations more efficient and agile, they also brought new sources of vulnerability as a result of keeping limited inventories and increased dependence on suppliers (Ponomarov and Holcomb, 2009; Daohai, 2012).

A relevant organizational structure is the collaborative business ecosystem which represents a socio-technical complex adaptive system, that leverages the benefits of sharing and collaboration, and embeds a high degree of agility. The notion of business ecosystem as proposed by Moore (1996) represents "*an economic community supported by a*

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foundation of interacting organizations and individuals … that produces goods and services of value to customers" and a "*biological metaphor that highlights the interdependence of all actors in the business environment, who 'co-evolve their capabilities and roles'* ". In Graça and Camarinha-Matos (2017) this notion is described as a form of a collaborative network, i.e., a particular case of a Virtual organizations Breeding Environment (VBE), and the term collaborative business ecosystem is introduced to emphasize the collaborative perspective. Within such an environment, the role of collaboration is related to the parties' willingness to interact and share, not only their profits but also risks (Soni et al., 2014). As such, business ecosystems are often pointed out as an adequate organizational structure to cope with unforeseen disturbances that can cause financial losses and in some cases firms' closures (Graça and Camarinha-Matos, 2017). It is however noted that collaboration also brings new sources of risk by opening the organization's borders (Camarinha-Matos, 2014). This naturally calls for new approaches to understand, measure, and respond to stressful conditions. However, completely eliminating disruptions is impossible, namely because most of them are of an exogenous nature. Organizations thus need procedures to reduce the likelihood of vulnerabilities to disruptions, such as, proactive plans to be executed in disaster readiness, response, and recovery. Furthermore, we must accept the unpredictability of complex systems' behavior and prepare for the unknown future, as systems are becoming more complex and interconnected (Dahlberg, 2015; McEntire, 2015).

In this context, the terms risk mitigation (management), disaster preparedness, recovery, resilience, robustness, and antifragility have become frequent keywords in the literature when dealing with disruptions (Zitzmann, 2014). In particular, resilience (Camarinha-Matos, 2014) and antifragility (Derbyshire and Wright, 2014) are two concepts that have been frequently used to describe important capabilities of firms to survive and thrive in unpredictable business environments.

Although there is no guaranteed way to avoid disruptions in business ecosystems, some companies overcome stressful situations better than others (Murino et al., 2011). For instance, Toyota was affected by a supply network disruption after the tsunami in 2011 because of the centralization of its supply chain in Japan. Conversely, General Motors was much less influenced, thanks to its decentralization strategy. The challenge for business managers is therefore to choose appropriate strategies against such threats, which depend on the type and phase of the "disaster" (Davarzani et al., 2011; Davarzani and Norrman, 2014).

In order to get an understanding of the current state and trends in the area, this article summarizes the findings of a literature survey on resilience and antifragility with a particular focus on collaborative business ecosystems. A set of strategies (enablers) against the effect of disruptions have been identified and categorized according to the phases of the disaster management process. A comprehensive taxonomy is proposed showing the link between resilience and antifragility-based strategies and the phase of coping with the disruption. Moreover, the most relevant capabilities (formative elements) of these strategies are also categorized. This research also attempts to identify tools, rules and other contributions from a multi-disciplinary perspective. Another contribution is the identification of illustrative examples of resilience and antifragility.

As such, this article is organized as follows. Section two presents the adopted research method and Section three first reviews the business ecosystem literature on disruptions classification and introduces core emergent concepts to deal with disruptions. Section four discusses the main findings of this survey. Finally, Section five provides some conclusions and suggestions for future work.

2. Survey approach

This study follows the systematic literature review (SLR) method (Kitchenham, 2004). SLR has been extensively used by many researchers in different fields as a systematic process to collect, evaluate, and synthesize all relevant studies on a topic of interest. Systematic Mapping (SM) is a lighter version of SLR that attempts to provide a map of a research area, structure a field of interest by categorizing papers in that domain and get an overview or a pictorial map of the field, and also identify trends as a basis for future research (Camarinha-Matos and Afsarmanesh, 2018). Our aim is to perform a survey and analysis of relevant literature on resilience and antifragility with a particular focus on collaborative business ecosystems. Since these concepts are emergent, publications in this area are less organized and still scattered; therefore, SM is the adequate approach to guide this analysis.

For this survey, the following research questions are set:

RQ1. What are emergent approaches to handle disruptions in business ecosystems?
RQ2. Which knowledge areas are contributing to this issue?
RQ3. Which are relevant examples of approaches to handle disruptions?

As mentioned above, this work aims at a multidisciplinary review to identify relevant approaches that may help business ecosystems cope with disruptive environments. The ISI Web of Science, Google Scholar, and SCOPUS are the main databases used to conduct the research. Searches were initially performed using a combination of keywords and sentences which were progressively updated as we got more insight into the area:

- Disruptions: disturbance / disruption / disorder / shock / stress / disaster / crisis/hazard.
- Collaborative organizations: business ecosystems / supply chains / disaster rescue networks.
- Emergent approaches to handle disruptions: resilience / antifragility.
- Domain: disaster management / disruption management / risk management / complex adaptive systems.
- Coping strategies: collaboration.
- Knowledge area: collaborative network / ICT / Management science.

Although the period for the search was initially set from 2010 to 2018, given the exploratory nature of the work, and also to referring some facts, it was necessary to follow the references and include some earlier reference works. At the first stage, "disruption" (and its synonyms), business ecosystem, supply chain, and collaborative networks were chosen as the initial search keywords to search published papers from 2010 to 2018. For instance, "*disruption* AND *business ecosystem,*" "*disruption* AND *supply chain,*" "*disruption* AND *collaborative networks.*" This initial search returned 300 results, which indicates that resilience and antifragility are emerging research approaches to handling disruptions in business ecosystems. At the second stage, the range of the research questions defined the main filtering criteria, which was first performed with a screening of the abstracts and quick browsing over the paper contents considering inclusion (articles directly related with the issues) and exclusion (articles that only have the keyword without discussion) criteria. As a result of this step, a total of 200 articles were kept as the basis for this exploratory research. At the third stage, the 200 papers were carefully reviewed, and unrelated papers were dropped. In the end, a total of 110 articles were used for this survey work.

3. Disruptions and related concepts in business ecosystems

Disruptions have been recognized as one of the critical issues in managing business ecosystems. In the literature "disruption", "disturbance", "disaster", "hazard", "black swan", "crisis", "catastrophic or traumatic event", "failure", "attack", "shock", and "X-Event (extreme event)" are often used interchangeably to refer to these threatening situations (Jüttner and Maklan, 2011; Monperrus, 2017). As such, different concepts have been used to describe the notion of disruption. For instance, (Wagner and Neshat, 2010) defines disruptions as "the trigger that leads to the occurrence of the risk" and according to Jüttner and Maklan (2011) disruptions "*imply a certain level of turbulence and uncertainty*". In Zhao et al. (2011) the authors state that disruptions "*affect the normal operations*" and they are either random or targeted. In this work, the term "disruption" is used according to the definition by Ellis (2010) as cited in Habermann et al. (2015) to indicate a "predictable or unpredictable event, which disrupts the normal operation and stability of a business" and can have a positive or negative impact on the business ecosystem.

In order to cope with such disturbances considerable attention by both academics and practitioners, has been given to the strategies designed to mitigate risks and respond efficiently to risk incidents, with two purposes: (1) recovering a system from sudden shocks, and (2) reducing the negative consequences of disruptions (Carvalho et al., 2012). Consequently, there has been a significant growth in the number of articles addressing disruptions in business ecosystems reflecting two main lines: (1) try to prevent risky events from occurring (reducing vulnerability), or (2) accept that we cannot precisely foresee disasters, but can prepare for plausible future scenarios and learn from past experiences, namely how disruptions affected the business and how firms responded to an unexpected disruptive event (Taleb, 2012).

Regarding the way systems respond to disruptions, a number of characteristics (Taleb, 2012; Chroust et al., 2016; Klibi et al., 2010) can be highlighted:

- **Fragility** – when systems are vulnerable and can be detrimentally destroyed or broken (fragile) in consequence of disruptions (Hespanhol, 2017). According to Taleb (2012), fragile things are typically large, over optimized, over-reliant on technology and do not have a built-in response system to disruption. Typically, if a fragile system breaks down, it does not recover (Chroust et al., 2016; Hespanhol, 2017).
- **Robustness** – when systems can sustain shocks and remain steady (robust) (Taleb, 2012). A robust system stays unchanged or uninfluenced by a disaster (Chroust et al., 2016). Achieving and maintaining robustness might be too complicated because of the involved costs and required energy.
- **Resilience** – when systems can absorb shocks and although temporarily changing, they recover from those shocks (Bhamra et al., 2011). The concept of resilience has been used over the last decade in different contexts, such as ecology, psychology, risk management, disaster management, safety engineering, supply chain management, and business ecosystems, which indicates the importance of also considering discipline-specific definitions (Bhamra et al., 2011; Dahlberg, 2015; Ponomarov and Holcomb, 2009). Etymologically, *resilience* comes from the Latin root word, *resilire*, which means to rebound and implies springing back (Russo and Ciancarini, 2017), representing systems' ability to recover from sudden shocks (Dahlberg, 2015), namely through absorption and adaptation (Dahlberg, 2015; Chroust et al., 2016). The affected system is able to return to an acceptable state, not necessarily the same as before (Chroust et al., 2016). In the case of complex adaptive systems, such as collaborative business ecosystems, resilience is related to adaptability and transformability capabilities, which leads to the notion of transformative resilience (Dahlberg, 2015). Transformative resilience is not merely about resistance to shock and conservation of existing structures, but it is also about the systems' ability to reorganize, reconfigure, restructure, and even reinvent when appropriate in response to disruptions.
- **Antifragility** – when systems absorb shocks and get better afterward (Taleb, 2012; Hespanhol, 2017). Since there is not really a word to describe a system that is exactly the opposite of "fragile", Taleb called it antifragile and introduced the concept of antifragility as a property beyond robustness and resilience (Russo and Ciancarini, 2017). According to Taleb (2012), the idea behind "antifragility" is to survive (even thrive) in the age of complexity and volatility when dealing with unknown randomness and disruptions (Taleb, 2012; Russo and Ciancarini, 2017; Hespanhol, 2017). He argues that "*antifragility and fragility are degrees on a spectrum, and we can almost always detect antifragility (and fragility) using a simple test of asymmetry: anything that has more upside than downside (convex) from random events (or certain shocks) is antifragile. Anything that acts reversely is fragile*" (Russo and Ciancarini, 2017). While a robust or resilient system resists failure and remains the same or recovers from failure, an antifragile system benefits from shocks, getting better (Lichtman et al., 2016; Hespanhol, 2017). Antifragility is therefore a highly desirable property, but its implementation might be too complicated, and the required components not yet well understood (Chroust et al., 2016).

Resilience and antifragility, as the most powerful approaches against disruptions in business ecosystems, are the focus of this study. Partial understandings and perspectives for these concepts have been developed in multiple disciplines and knowledge areas, as summarized in Tables 1 and 2.

Despite the rising interest in these concepts, a widely agreed definition for them has not been stated yet, as reflected in the given examples. Nevertheless, we can identify three dimensions for the concept of resilience:

(1) Capacity of a system to rebound from trauma and recover (i.e., stability);
(2) Capability of a system to maintain a desirable state (i.e., bouncing back to a new equilibrium condition or an accepted state); and
(3) Capacity of a system to withstand stress with the focus on persistence thresholds (i.e., gradual adaptation and transformation).

These dimensions reflect an earlier notion of resilience, focused on consistent behavior of the system and its absorptive coping capacity. Recently the concept has been evolving to represent an adaptive and even transformative capacity, by concentrating on non-linear complexity and multidimensional stability of systems (multi-equilibria), which partially overlaps with the notion of antifragility.

Antifragile systems, on the other hand, are those which not only survive shocks but also actively "employ" them to become stronger. Antifragility is thus a property of systems that adapt to volatility and learn from experiences, faults, and incidents, for instance, through a "learning by doing" process how to thrive as conditions evolve (i.e., adaptability and evolvability). This means, going beyond the traditional target of resilience, aiming improvement and thus bringing a new perspective of sustainability and generativity to complex adaptive systems.

The relationship between the above notions is illustrated in Fig. 1.

4. Results and discussion

In this section we present the main findings of the performed survey regarding approaches, contributing knowledge areas, and representative examples.

4.1. Emerging Approaches to handle disruptions in business ecosystems

According to Jüttner et al. (2003), disruption sources, disruption drivers that turn disruptions into consequences, and strategies to address the disturbances are a 3-fold construct. Furthermore, it is also important to consider the internal capabilities of the business ecosystem that can be activated according to planned strategies in reaction to

Table 1
Resilience.

Focus Area	Definition/Description	References
Materials Science	▪ Property of a material to return to its original shape after a deformation caused by stress.	(Murino et al., 2011; Vecchiola et al., 2013)
Ecology	▪ Rate at which a system returns to equilibrium after a perturbation or disruption. ▪ Ability to absorb a disruption and self-reorganize while undergoing change but still maintaining system's identity (structure, interrelationships and functions).	(Bhamra et al., 2011; Soni et al., 2014; Madni and Jackson, 2009; Soni et al., 2014)
Socio–ecology	▪ Capacity of natural and social systems to absorb disturbances while preserving the same function, structure, identity, and feedbacks.	(Rochas et al., 2015)
Economy	▪ "*Inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses*", i.e. the ability to withstand, adapt, reconstruct and recover from a severe shock or stress without losing the capacity of retain prosperity.	(Madni and Jackson, 2009; Rochas et al., 2015; Ponomarov and Holcomb, 2009; Rochas et al., 2015)
Social Sciences	▪ Coping, adaptive, and participative capacities of social systems to face external stresses and disturbances.	(Lorenz, 2013)
Psychology	▪ Self-renewal and adaptation capacity of individuals or groups to cope with stress and continue functioning and developing.	(Bhamra et al., 2011; Soni et al., 2014; Madni and Jackson, 2009)
Business	▪ Ability of a company to adapt changes and cope with unexpected events, exploiting opportunities to gain competitive advantage and grow in turbulent markets.	(Pettit et al., 2013; Murino et al., 2011; Vecchiola et al., 2013)
Supply Chain	▪ Ability to prepare for unexpected events, respond to and recover from them, maintaining the continuity of operation. ▪ Capability to recover the "*original operating status before a disruption or to move to a new, more desirable one, after experiencing a disturbance, and avoiding the occurrence of failure modes*". ▪ Speed with which a chain can return to normal working after a disruption.	(Carvalho et al., 2012; Ponomarov and Holcomb, 2009; Jüttner and Maklan, 2011; Carvalho et al., 2012; Barroso and Machado, 2011)
Communities	▪ Capacity to withstand disasters, minimize their impact, and seize the opportunity to "*improve living standards to transform livelihood systems while sustaining the natural resource base*", by its capacity for collaboration, negotiation, self-organization, shared awareness, and problem solving.	(Rochas et al., 2015; Vecchiola et al., 2013; Frankenberger et al., 2013)
Infrastructure Systems	▪ Ability to provide critical functions and services continuously by predicting, withstanding, adapting, and recovering (back to its original state) from the effects of a disruptive event.	(Vecchiola et al., 2013)
Disaster Management	▪ "Ability of a system, community or society to resist, absorb, accommodate and quickly recover from hazards including preservation and restoration of its essential structures and functions."	(Chroust and Aumayr, 2017)
Organizations	▪ Capability to sustain continuity of operations through adaptive capacity in presence of disturbances and unpredicted changes.	(Bhamra, 2011; Ponomarov and Holcomb, 2009; Tang, 2006)
Systems Thinking	▪ Ability to effectively "reduce both the magnitude and duration of the deviation from targeted system performance levels." ▪ Capacity to bounce back to dynamic stability (acceptable state, even if not the same as before) after a disturbance.	(Chroust and Aumayr, 2017)
Complex Systems	▪ Ability to absorb and adapt to disruptions and bounce not back but forward to more advanced levels better suited for future hazards.	(Dahlberg, 2015; Madni and Jackson, 2009)
Physical Systems	▪ "*Speed at which a system returns to equilibrium after displacement, irrespective of oscillations*".	(Bhamra et al., 2011)
Engineering	▪ Ability at all levels of systems or organizations to become more agile and proactive in assessing risks, anticipating changing risks' shape, and making the changes necessary to prevent their failure. ▪ Ability of systems to resist external influences and return to well-defined equilibrium states.	(Vecchiola et al., 2013; Lorenz, 2013)
Computing	▪ Ability of a system to maintain the quality of service delivery and being trusted when facing attacks (i.e., using self-adaptation to recover from the failures).	(Russo and Ciancarini, 2017; Vecchiola et al., 2013; Guang et al., 2014)
Networks	▪ Fault tolerance capability of a network, e.g. communications, water, or energy systems, to provide and maintain an acceptable level of service in face of disruptions to normal operation.	(Madni and Jackson, 2009)

disruptions. Through learning mechanisms, strategies can also be improved. These ideas are illustrated in Fig. 2 and further detailed below.

4.1.1. *Disruption Sources and drivers*

The literature on business ecosystems shows that disruptions can arise from many sources which can be broadly classified into two categories (Kumar et al., 2009):

(1) Endogenous disruptions, which result from failures occurring within the ecosystem such as, for example, lack of skills, materials, etc.
(2) Exogenous disruptions which are due to constraints imposed from outside the ecosystem such as weather, regulations, etc.

We suggest further dividing endogenous disruptions into: (1) network related risks in general, comprising any uncertainties arising from the interactions between organizations within the business ecosystem, (2) organization related risks, such as failures in internal operations (product/service, process/control), material flow, financial flow, and information flow, and decision making related risks, (3) supply chain related risks, including supply/demand side risks, such as supplier bankruptcy, distributed or transport providers failures, etc., (4) security-related disasters including malicious threats (intentional and unintentional) caused by human behavior such as theft, vandalism, sabotage, industrial espionage, counterfeiting, fire, cyber-attack, etc., and also failures in the infrastructure of the network, such as fixed and mobile assets (equipment, truck, boat, planes, etc.), IT assets (software, hardware, processing and communication systems), and financial risks (low financial stability of any member or excessively risky investment).

Similarly, exogenous disruptions can be classified into: (1)

Table 2
Antifragility.

Focus Area	Definition/Description	References
Biology	▪ Capability of a system to "*become stronger when stressed. E.g. Muscle, for example, becomes stronger when stressed through activity and exercise and, ironically, atrophies when it is not used*".	(Jones, 2014; Danchin et al., 2011)
Organizations	▪ Capability to regenerate, prosper, and "*improve in response to unpredictability, volatility, randomness, chaos and disturbance*". Errors and randomness are essential for organizations to improve, depriving them from volatility and shocks will weaken the system. ▪ The ability of organizations to learn and improve from failures.	(Taleb, 2012; Jaaron and Backhouse, 2014)
Supply Chain	▪ An anti-fragile supply chain understands uncertainty and affects as an opportunity to flourish.	(Zitzmann, 2014)
Communications	▪ Capability of a communications system to improve performance due to a system's stressor, attack, or harsh condition.	(Lichtman et al., 2016)
Disaster Management	▪ Ability to create new conditions of fitness for a system as a result of disasters.	(Chroust and Aumayr, 2017)
Systems Thinking	▪ "*Capacity of an adapting and/or evolving system to bounce back to dynamic stability after a disturbance. In a more general meaning, resilience* [antifragility] *includes system's ability to create new conditions of fitness for itself whenever necessary*".	(Chroust and Aumayr, 2017; Taleb, 2012)
Complex Systems	▪ Capability to not only remain unaffected by random and unpredicted changes, but also manage to take advantage of them.	(Taleb, 2012)
Intelligent/Cognitive Systems	▪ Ability to learn from experience, to adapt to unforeseen conditions, and to improve performance in face of adversity.	(Jones, 2014)
Information Systems	▪ Ability to extract the intrinsic value of errors and learn from them, leading to continuous system improvements. E.g., "*by allowing a small fraction of its devices to be infected, a networked system can be made antifragile to infectious malware with unknown and time-varying spreading mechanisms*".	(Gorgeon, 2015)
Computing	▪ Antifragile systems become stronger aftershocks. Failure provides learning opportunities to strengthen the system.	(Guang et al., 2014; Abid et al., 2014)
Infrastructure Networks	▪ Performance improvement as a result of exposure to stressors, shocks, or disruptions. Indeed, an antifragile system extracts the "intrinsic value" of failures.	(Fang and Sansavini, 2017)
Software Engineering	▪ An antifragile system "learns" to "*better counter similar disturbances in future, possibly becoming fault tolerant or even robust*". ▪ "Anti-fragile software extracts the intrinsic value of errors, learns from them" and grows stronger after each successive stressor, disturbance, and failure.	(Chroust and Aumayr, 2017; Monperrus, 2017; Russo and Ciancarini, 2017)

environment-related risks in general, that arise from the business ecosystem–environment interaction, (2) natural disasters, such as epidemic diseases, hurricanes, floods, tornadoes, etc., (3) socio-economic risks, such as political risks (embargoes, war, terrorism, etc.), economic risks (recession, currency fluctuation, high bank interests and funds shortage, etc.), and policy risks (regulatory, legal, and bureaucratic), (4) infrastructure risks, including global infrastructure breakdowns such as the internet, power grids, roads (railways, shipping lanes, and flight path), etc. Table 3 provides a summary of these disruption sources according to the literature.

Additionally, business ecosystems are profoundly affected by the accumulation of several pressure factors from the surrounding environment that increase the level of risk exposure for the ecosystem (Jüttner et al., 2003). Based on this survey, we identified five significant types of pressure factors, which we call fundamental drivers, and that make business ecosystems susceptible to disruptions:

(1) Social and environment pressures,
(2) Demand pressures,
(3) Pressures to lower costs,
(4) Dependency pressures, and
(5) Network structure constraints.

Table 4 summarizes these disruption drivers according to the literature.

4.1.2. Disruption Handling strategies

To help a business become less vulnerable to disturbances, adequate coping strategies must be defined (Tomlin, 2006). Traditional risk management approaches were designed for a context of relatively stable business environments. Moreover, traditional approaches require risk identification, and quantification, which rely on past experimental data. Therefore, such methods are not useful to handle low probability,

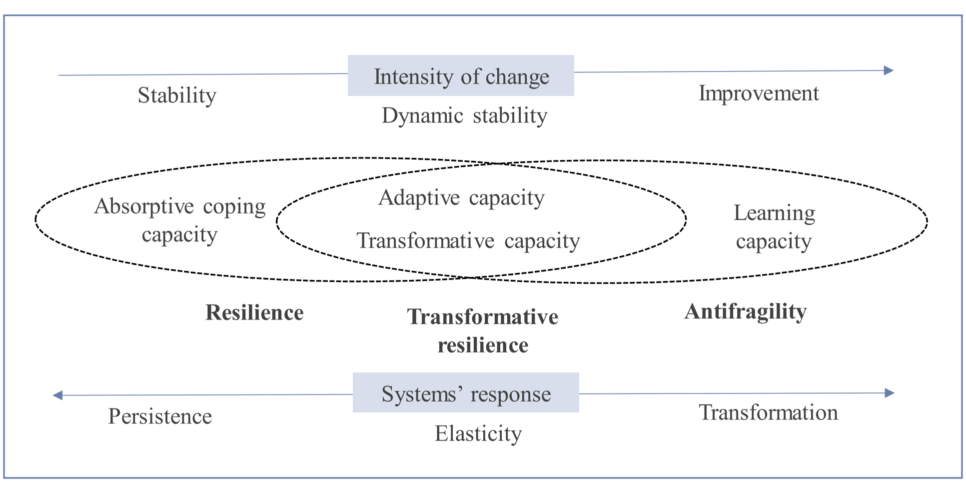

Fig. 1. Resilience, transformative resilience, and antifragility.

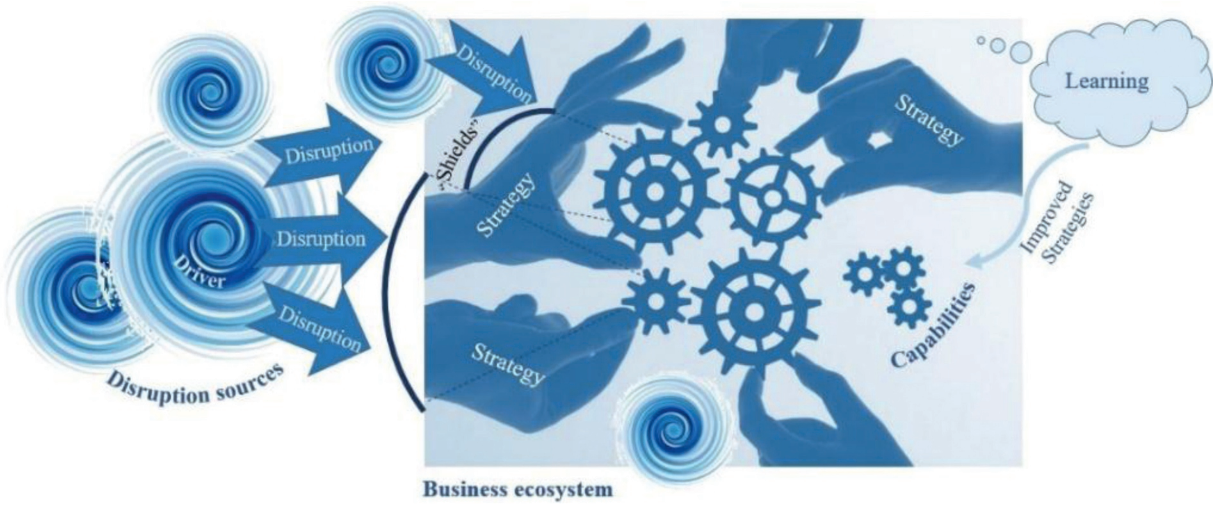

Fig. 2. Disruption sources, coping strategies and capabilities.

high impact disruptions. On the other hand, traditional strategies are cost-based and narrow-focused and therefore may cause more vulnerability in businesses dealing with unforeseeable events (Pettit et al., 2013; Fiksel et al., 2015). Companies which use traditional strategies like just-in-time and lean manufacturing in collaborating with fewer suppliers to control inventory can increase risk levels during disruptions. For example, companies like Toyota that followed the lean manufacturing approach were seriously affected by Japan's tsunami because of the lack of buffer capacity. This trend has changed in recent decades as organizations managing large, global, competitive, and complex chains need to consider broadly-focused approaches to proactively and reactively address various threats (Pettit et al., 2013; Schmitt, 2011). Resilience-focused approaches enhance traditional risk management strategies as they focus on coping with unpredictable uncertainties (Pettit et al., 2013). Antifragility is also based on the fundamental assumption that not all uncertainties can be prevented, and goes one step further aiming at businesses that prepare for change by becoming as adaptive, responsive, and flexible as possible (Derbyshire and Wright, 2014). For unavoidable disruptions, the emphasis here is to reduce the effect of the disturbances and transform them into business opportunities.

In order to get a better contextualized perception of strategies and their applicability, we suggest a categorization according to three general phases of disaster management: Readiness, Response, and Recovery:

- **Readiness** - ability of a system to prevent disruptions, maintaining the planned level of operations (Craighead et al., 2007; Ponomarov and Holcomb, 2009). It implies efforts to increase preparedness for disaster response and recovery (McEntire, 2015), involving investment in advance of a disruption (Klibi et al., 2010). "Readiness" thus relates to a set of activities to detect and eliminate the source of possible disruptions or reduce (mitigate) their negative impact (McEntire, 2015). These activities include anticipatory measures and actions, resource acquisition, community education, specifying roles to deal with disruption, etc. (McEntire, 2015). This phase leads to mitigation strategies. Mitigation strategies are more proactive (act before a disruption) and focus on avoiding disruptions. As such, inventory control strategies related to ordering and stocking decisions can be considered proactive strategies (Tomlin, 2006; Wieland and Wallenburg, 2012). Examples of risk mitigation include increasing security, facility location, tracking the financial health of suppliers, and learning from the experience of others (Chroust et al., 2016; Natarajarathinam et al., 2009). According to Mojtahedi and Oo (2017) this phase includes developing policies for training and education, budgeting, maintaining supplies, predicting the likelihood of events and warning, identifying and assessing disruption and developing efficient collaboration procedures with suppliers by forming consortia and sharing information. Additionally, (Ponomarov and Holcomb 2009) introduces other relevant strategies to this phase such as logistics "quality, efficiency, cost minimization, risk hedging capabilities, backups of systems and processes, systematic contingency planning, information technology upgrades, and supply chain relationship building."
- **Response -** concerned with the immediate actions taken after a disaster occurs, aiming to protect life and property of a community or business ecosystem (McEntire, 2015; Natarajarathinam et al., 2009). Response implies minimizing the time to react to disruptions, prepare for the beginning of the recovery stage by utilizing the plans created during the readiness stage and also reorganizing resources quickly (Craighead et al., 2007; Ponomarov and Holcomb, 2009). "Response" thus relates to rapidly bringing the system into a temporarily acceptable operational state, offering contingency strategies in disaster management (Chroust et al., 2016; Natarajarathinam et al., 2009). Contingency strategies are mainly reactive (triggered by the occurrence of a disruption) and focus on increasing the responsiveness capability in face of a disruption. Strategies that involve product or supplier substitution such as demand management, and multi-sourcing are reactive strategies (Tomlin 2006; Wieland and Wallenburg, 2012). Response includes developing policies for providing information, implementing effective collaboration, activating the disaster emergency plans, estimating economic damage, logistics management, employment and mobilization of resources (Mojtahedi and Oo, 2017; McEntire, 2015). Further strategies related to this phase are listed in Ponomarov and Holcomb (2009) including "timeliness, postponement, flexibility, agility, risk sharing, and information sharing."
- **Recovery** - related to the activities aiming to return the disturbed system to a pre-disruption or normal operational state or, preferably, to improved levels of operation by redesigning the business processes, learning from the experiences, and benefiting from opportunities (Ponomarov and Holcomb, 2009; McEntire, 2015; Craighead et al., 2007). "Recovery" is thus the long-lasting stabilization and restoration phase (Chroust et al., 2016; Natarajarathinam et al., 2009). According to Mojtahedi and Oo (2017), this phase includes executing the plans for post-disaster, providing business assistance, applying quick mobilization, rebuilding infrastructures, repairing and restoring functions, and identifying lessons learned and best practices. Further strategies related to this stage are suggested in Ponomarov and Holcomb

Table 3
Disruption sources.

Disruption Sources	Endogenous Disruptions (Network-related)			
	Network-related risks (General)	**Organization related risks**	**Supply chain related risks**	**Security-related risks**
	(Faisal et al., 2006; Ponomarov and Holcomb, 2009; Jüttner et al., 2003; Kumar et al., 2009; Lin and Zhou, 2011; Natarajarathinam et al., 2009)	***Internal Operations*** (Habermann et al., 2015; Madni and Jackson, 2009; Chowdhury and Quaddus, 2015; Manuj et al., 2008; Wakolbinger and Cruz, 2011; Torabi et al., 2015; Tummala and Schoenherr, 2011) *Organizational* (Faisal et al., 2006; Jüttner et al., 2003) *Process/Control* (Murino et al., 2011; Christopher et al., 2011; Briano et al., 2010) *Product/service* (Tummala and Schoenherr, 2011; Diabat et al., 2012) ***Material Flow*** (Tang and Nurmaya, 2011) ***Financial Flow*** (Tang and Nurmaya, 2011) ***Information Flow*** (Tang and Nurmaya, 2011)	***Supply Side*** (Murino et al., 2011; Davarzani et al., 2011; Davarzani and Norrman, 2014; Habermann et al., 2015; Chowdhury and Quaddus, 2015; Manuj et al., 2008; Tummala and Schoenherr, 2011; Christopher et al., 2011; Briano et al., 2010; Diabat et al., 2012; Bode et al., 2013) ***Demand Side*** (Murino et al., 2011; Habermann et al., 2015; Jaaron and Backhouse, 2014; Chowdhury and Quaddus, 2015; Manuj et al., 2008; Tummala and Schoenherr, 2011; Christopher et al., 2011; Briano et al., 2010; Diabat et al., 2012)	***Malicious Threats*** (Bhamra et al., 2011; Torabi et al., 2015) *-Intentional acts* (Davarzani et al., 2011; Davarzani and Norrman, 2014; Klibi et al., 2010) *- Intellectual property* (Tang and Tomlin, 2008) *-Unintentional acts* (Daohai, 2012; Klibi et al., 2010) *- Negligence* (Daohai, 2012) ***Infrastructure Breakdowns*** (Bode et al., 2013) *- Equipment* (Bhamra et al., 2011; Tummala and Schoenherr, 2011) *- IT assets* (Diabat et al., 2012)
Disruption Sources	**Exogenous Disruptions (Environment-related)**			
	Environment related risks (General)	**Natural Disasters**	**Socio-economy risks**	**Infrastructure-related risks**
	(Murino et al., 2011; Faisal et al., 2006; Ponomarov and Holcomb, 2009; Jüttner et al., 2003; Kumar et al., 2009; Lin and Zhou, 2011; Natarajarathinam et al., 2009; Christopher et al., 2011; Briano et al., 2010; Diabat et al., 2012)	***Geological*** (Bhamra et al., 2011; Daohai, 2012; Davarzani et al., 2011; Davarzani and Norrman, 2014; Zhao et al., 2011; Klibi et al., 2010; Madni and Jackson, 2009; Jaaron and Backhouse, 2014; Chowdhury and Quaddus, 2015; Wakolbinger and Cruz, 2011; Torabi et al., 2015; Diabat et al., 2012) ***Biological*** (Bhamra et al., 2011)	***Political Risks*** (Bhamra et al., 2011; Daohai, 2012; Zhao et al., 2011; Madni and Jackson, 2009; Wakolbinger and Cruz, 2011) ***Economic Risks*** (Bhamra et al., 2011; Zhao et al., 2011; Madni and Jackson, 2009; Jaaron and Backhouse, 2014; Chowdhury and Quaddus, 2015) *- Regional economic crises* (Rocha, 2014) ***Policy risks*** (Bode et al., 2013)	***Infrastructure Breakdowns*** (Chowdhury and Quaddus, 2015)

Table 4
Disruption drivers.

Driver	Disruption
Social and environment pressures	- Changes in social and ecological environment (Wagner and Neshat, 2010; Tummala and Schoenherr, 2011; Rocha, 2014) - Inequality between countries and increasing gap among social classes (Chowdhury and Quaddus, 2015; Rocha, 2014) - Demographic shifts (Rocha, 2014) - Natural resource scarcity (Rocha, 2014) - Environmental degradation (Rocha, 2014) - Changes in regulations for environmental protection and working conditions (Rocha, 2014)
Demand pressures (Complexity of market pressures)	- Shorter product lifecycles (marketing) (Ponomarov and Holcomb, 2009; Zitzmann, 2014; Wagner and Neshat, 2010) - Increased volatility of demand (Pettit et al., 2013; Ponomarov and Holcomb, 2009; Wagner and Neshat, 2010; Rocha, 2014) - Emergence of new markets (Tummala and Schoenherr, 2011) - Low in-house production (Wagner and Neshat, 2010) - Competitive environment (Chowdhury and Quaddus, 2015; Tummala and Schoenherr, 2011) - Technological/competitive innovation (Pettit et al., 2013; Zitzmann, 2014; Wagner and Neshat, 2010; Rocha, 2014)
Pressure to lower cost (Focus on efficiency)	- Focus on improving efficiency (Zitzmann, 2014; Hendricks and Singhal, 2012) - Trends like lean manufacturing (Daohai, 2012) - Focusing on reducing inventory (Daohai, 2012; Hendricks and Singhal, 2012) - Reduced number of suppliers (Pettit et al., 2013; Daohai, 2012; Wagner and Neshat, 2010)
Dependency pressures	- Customers' dependency (Wagner and Neshat, 2010) - Dependency on key suppliers (Wagner and Neshat, 2010) - Growing dependency on complex technological systems (Rocha, 2014)
Network structure constraints (Node criticality)	**• Specialization and geographical concentration:** - Single sourcing (special sources) (Hendricks and Singhal, 2012) - Centralized distribution/production (Pettit et al., 2013) - Specialized factories (Pettit et al., 2013) **• Globalization and outsourcing:** - Acceleration of globalization (Ponomarov and Holcomb, 2009; Daohai, 2012; Zitzmann, 2014; Habermann et al., 2015; Tummala and Schoenherr, 2011; Rocha, 2014) - Increased reliance on outsourcing (Pettit et al., 2013; Daohai, 2012; Wagner and Neshat, 2010; Hendricks and Singhal, 2012) - The complexity of global supply chains (Daohai, 2012; Zitzmann, 2014; Habermann et al., 2015; Hendricks and Singhal, 2012) - Long, complex, and global design of today's supply chains (Daohai, 2012; Habermann et al., 2015)

(2009) such as "cycle-time reduction, delivery competency, customer service, the efficiency of warehouse operations, knowledge management, and highly integrated systems and processes."

Table 5 presents a list of the identified resilience and / or antifragility aiming strategies, also indicating to which phases they mostly relate. The classification according to these phases is our proposal as a result of a careful analysis of the literature. Nevertheless, it should be noted that the filled boxes only intend to show the main phase of applicability, although in some particular cases it could be that a specific strategy could also be applied to a different phase.

Resilience aiming strategies are those that help a business to cope with unexpected events and survive in the long term (Pettit et al., 2013), but without necessarily leading to an improvement. For instance, *buffering*, which attempts to gain stability by establishing safeguards that protect a firm from disturbances, is a resilience aiming strategy to prevent the possible disruptions (Derbyshire and Wright, 2014). Similarly, *insurance*, which refers to financial risk sharing as it transfers the risk of compensable loss to the insurer, is a resilience-based strategy (Tomlin, 2006). According to Taleb (2012), the best criteria for detecting antifragility is using a simple test of asymmetry: ensuring that the potential upside (gain) is higher than potential downside (loss) as a consequence of the exposure to and experience of stressors. Therefore, the *Barbell* strategy, which demonstrates an antifragile balance by investing most of the assets conservatively (staying robust to negative disruptions) while taking risks with the rest (open to positive disruptions), is a useful strategy to invest in advance of a disaster. Similarly, *hormesis*, which refers to growth through adapting to a reasonable dose of a harmful stressor, is an antifragility aiming strategy (Taleb, 2012). Some strategies cover both concepts of resilience and antifragility. For example, *collaboration* is a resilient strategy as it contributes to reduce uncertainty and increase the system's capability to respond to unforeseen circumstances (Pettit et al., 2013). On the other hand, *collaboration* could also be considered as an antifragility-based strategy as it reduces the risk of failing while emphasizing optionality and increasing the potential opportunities for success. Therefore, the boxes in the Resilience / Antifragility column of Table 5 represent the authors' perception as acquired from the analyzed literature.

To provide an organized "decision space" for managers and decision-makers of organizations in business ecosystem, following our previous research (Ramezani and Camarinha-Matos, 2019), Fig. 3 presents a comprehensive overview of the identified disruption-coping strategies classified according to 6 meta-levels: (1) "discovering" (understanding the environment), strategies to detect critical sources of disruptions and estimate how the system is expected to change with disruption, e.g. "mapping", (2) "avoiding", strategies to prevent threatening situations, e.g. "buffering", (3) "do nothing", strategies to accept the risk of disruption, e.g. "wait-and-see", (4) "reducing", strategies to mitigate vulnerability and negative consequences, e.g. "information sharing", (5) "managing", strategies to manage system complexity, e.g. "contingency planning", and (6) "learning and adapting", strategies to solve problems creatively, e.g. "trial-and-error".

4.1.3. Capabilities to enhance resilience and antifragility

Resilience and antifragility are often used in relation to other concepts such as survivability (Murino et al., 2011), adaptability, robustness, and sustainability (Camarinha-Matos, 2014) that represent base support capabilities. According to Davarzani and Norrman (2014) there is a large number of overlapping terms for these capabilities that enable a business ecosystem to become resilient or antifragile. In fact, these factors focus on reducing fragility and harnessing antifragility (Gorgeon, 2015). For instance, in Schmitt and Singh (2012) the authors underline that creating redundancy and enhancing flexibility in the system reduce the likelihood of disruptions and make it more able to face disruptions. For instance, extra engines can be used for a plane in

Table 5
Strategies to handle disruptions.

Strategy	Readiness/Response/Recovery	Description	Resilience	Antifragility	References
Acceptance	□ ■ □	Simply accepting the disruption risk, and the associated cost; typically, favored when (1) the cost of coping with disruptions outweighs the losses from accepting them; (2) disruption risk is low; or (3) mitigation costs are very high. - Wait and see	■	□	(Chroust and Aumayr, 2017; Tomlin, 2006; Schmitt and Tomlin, 2012)
Barbell	■ □ □	Eliminating the exposure to losses due to disruptions by investing most of the assets conservatively in extremely safe instruments while taking risks with the remaining in areas with potentially large-scale positive outcomes.	■	■	(Taleb, 2012; Derbyshire and Wright, 2014; Hespanhol, 2017; Devendorf et al., 2017)
Buffering	■ □ □	Attempting to gain stability through establishing safeguards that protect businesses from disturbances. Examples: - Safety stock - holding buffer stocks to reduce the risk of stock out. - Supplier backups - using multiple suppliers to guarantee availability. - Capacity buffer (e.g. slack capacity, excess capacity) -setting reserve capacity to avoid shortages during peak periods. - Safety lead times – to allow more flexibility.	■	■	*Buffering* (Derbyshire and Wright, 2014; Danchin et al., 2011) *Safety stock* (Diabat et al., 2012; Tomlin et al., 2011) *Stockpile inventory* (Tomlin and Wang, 2011; Van Kampen et al., 2010) *Strategic stock* (Tang, 2006) *Backup supply* (Chowdhury and Quaddus, 2015; Tomlin and Wang, 2011; Schmitt and Tomlin, 2012) *Backup capacity* (Chowdhury and Quaddus, 2015) *Capacity strategy* (Pettit et al., 2013; Ponomarov and Holcomb, 2009; Chowdhury and Quaddus, 2015) *Safety lead times* (Kampen et al., 2010; Glock and Ries, 2013)
Collaboration	■ ■ ■	Ability to work effectively with other entities to better achieve common or compatible goals, which helps to manage disruptions effectively. Collaboration contributes to reduced uncertainty and increase system's response capability in time of crisis. Examples: - Information sharing. - Risk sharing. - Building trust among partners (reducing functional conflicts and enhancing integration and decision-making under uncertainty and ambiguity). - Negotiation. - Plug and play teaming- the capability of a team to split in two to work in parallel in time of a crisis. - Product Lifecycle Management (enabling collaborative creation, management, dissemination, and use of product-related information.	■	□	*Collaboration* (Pettit et al., 2013; Faisal et al., 2006; Carvalho et al., 2012; Ponomarov and Holcomb, 2009; Barroso and Machado, 2011; Chowdhury and Quaddus, 2015; Wakolbinger and Cruz, 2011; Diabat et al., 2012; Tang and Nurmaya, 2011; Hendricks and Singhal, 2012; Jassbi et al., 2015) *Information sharing* (Faisal et al., 2006; Carvalho et al., 2012; Ponomarov and Holcomb, 2009; Barroso and Machado, 2011; Wakolbinger and Cruz, 2011) *Risk sharing* (Faisal et al., 2006; Ponomarov and Holcomb, 2009; Soni et al., 2014; Jüttner and Maklan, 2011; Carvalho et al., 2012; Manuj et al., 2008; Wakolbinger and Cruz, 2011) *Building trust* (Faisal et al., 2006; Soni et al., 2014) *Negotiation* (Chikumbo and Norris, 2015)

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Table 5 (*continued*)

Strategy Readiness/Response/Recovery	Description	ResilienceAntifragility	References
			Plug and play teaming (Faraj and Xiao, 2006) *PLM* (Pettit et al., 2013; Murino et al., 2011)
Cost Minimization ■ □ □	Focus on cost reduction through continuous elimination of waste (efficient use of resource) or activities which do not add value and may, in some cases, be the cause of disruptions. On the other hand, this strategy may be in conflict with others, like buffering.	■ □	(Ponomarov and Holcomb, 2009; Kumar et al., 2009; Diabat et al., 2012)
Customer Servicing □ □ ■	Engaging customers in a collaborative conversation in a trusted, transparent, responsiveness business environment.	■ □	(Ponomarov and Holcomb, 2009; Chowdhury and Quaddus, 2015; Schmitt, 2011)
Creating Disruption Management Culture ■ □ □	Establishing a culture that addresses a broad variety of attitudes of members of an organization on decision making about disruptions and vulnerability management and related topics such as compensation, coping strategy, responsibilities.	■ ■	(Soni et al., 2014; Barroso and Machado, 2011; Jüttner et al., 2003; Christopher et al., 2011)
Crisis Management ■ ■ ■	Process by which an organization deals with disruptive events (before, during, and after occurrence). Some techniques: - Business Continuity Management (BCM) - a process that identifies possible risks, and their impact on a firm and provides a roadmap for building resilience. - Contingency Planning - designed to ensure that organizations are ready to respond to and restore operations after unexpected disruptions. - Disaster Rescue Network - disaster recovery network with the ability to face unpredictable events, recover quickly after attack and start to operate efficiently.	■ ■	(Chroust and Aumayr, 2017; McEntire, 2015; Fang and Sansavini, 2017; Fiksel et al., 2015; Schmitt and Tomlin, 2012; Tomlin and Wang, 2011; Becken and Hughey, 2013) *Business continuity* (Bhamra et al., 2011; Zitzmann, 2014; Torabi et al., 2015; Craighead et al., 2007) *Contingency Planning* (Ponomarov and Holcomb, 2009; Diabat et al., 2012; Ruiz-Torres et al., 2013) *Disaster Rescue Network* (Becken and Hughey, 2013; Jassbi et al., 2015)
Demand Managing □ ■ □	To improves capability to better respond to unpredictable demand changes by product substitution through different strategies of price promotions, and incentives. E.g.: - Risk pooling, managing demand uncertainty through centralization of inventory. - Demand switching, providing incentives for a customer to purchase a different product if desired one is unavailable. - Aligning incentives & revenue sharing, like Profit sharing (with suppliers), revenue management (dynamic pricing and promotion), pricing mechanisms (influence customers to choose products that are widely available), and economic supply incentives. - Silent product rollover, in which new products are leaked slowly into the market. - Dynamic assortment planning. Influencing consumer product choice and customer demand by revisiting assortment decisions (ex: the location and number of product items on the shelves).	■ □	*Demand managing* (Sodhi and Tang, 2012; Tang, 2006; Tomlin, 2006; Tomlin and Wang, 2011; Schmitt and Singh, 2012) *Risk pooling* (Park et al., 2010; Mak and Shen, 2012) *Demand Switching* (Fiksel et al., 2015) *Aligning incentives & revenue sharing* (Faisal et al., 2006; Soni et al., 2014; Sodhi and Tang, 2012; Tang, 2006; Fiksel et al., 2015) *Profit sharing* (Wakolbinger and Cruz, 2011) Pricing strategy (Sodhi and Tang, 2012) *Silent product rollover* (Sodhi and Tang, 2012) *Dynamic assortment planning* (Sodhi and Tang, 2012)
Effectuation ■ ■ □	Adopting principles that entrepreneurs use for opportunity identification and new venture creation in situations of uncertainty to help decision-making to employ in situations of uncertainty caused by disruptions.	□ ■	(Derbyshire and Wright, 2014)
Exploring Eustress ■ □ □	Causing positive forms of stress that can have a beneficial effect on system. E.g.:	□ ■	*Hormesis*

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Table 5 (*continued*)

Strategy Readiness/Response/Recovery	Description	Resilience Antifragility	References
	- Hormesis / Mithridatization: When a small dose of a harmful substance or agent is beneficial to the system, protecting it from stronger doses in future exposure.		(Taleb, 2012; Dahlberg, 2015; Derbyshire and Wright, 2014)
	- Muscle hypertrophy: Increasing the size of a muscle under repeated loads, and demanding conditions, which cause an adaptive response of the muscle cells and improve their ability to generate force or resist fatigue.		*Hypertrophy*
	- Shockwave trophy: creating capillary micro ruptures in tendon and bone in order to accelerate the healing process of the damaged tissue structure.		(Taleb, 2012; Benson, 2013) *Mithridatization* (Taleb, 2012)
Forecasting ■□□	To predict market demand, etc. to avoid damaging consequences and improve the chances for survival.	■□	(Pettit et al., 2013; Chroust and Aumayr, 2017; Chroust and Aumayr, 2017; Murino et al., 2011; McEntire, 2015; Madni and Jackson, 2009; Chowdhury and Quaddus, 2015; Hendricks and Singhal, 2012; Becken and Hughey, 2013)
Fault Injection ■□□	A test-based approach for evaluating the dependability of a system by injecting faults not only during the design phases but also during the prototype and operational steps. This helps in identifying and understanding potential failures, and tolerable operating conditions thus inducing fault isolation, and reconfiguration and recovery capabilities. E.g.: Simian Army (Ex: Netflix), GameDay.	■■	(Monperrus, 2017; Russo and Ciancarini, 2017; Gorgeon, 2015; Abid et al., 2014; Tseitlin, 2013)
Fail Fast ■□□	To quickly detect vulnerabilities and learn from problems to prevent propagating failures - a system can fail early by inducing artificial failures when the impact is small.	□■	(Hole, 2016a)
Fail often ■□□	Trying many brave ideas with experiments that are designed to minimize the impact of failures.	□■	(Abid et al., 2014)
Feedback Mechanism □□■	A system with a feedback loop can control, alert, and improve its current status by comparing with reference values. The negative feedback mechanism maintains the system's stability in a volatile environment.	□■	(Devendorf et al., 2017; Verhulst, 2014)
Government Lobbying □■□	Attempting to influence decisions made by the government, e.g. to mitigate the impact of risks that can have a long-lasting effect.	■□	(Diabat et al., 2012)
Graceful Degradation □■□	To allow maintaining as limited functionality a possible when disruptions happen to prevent a catastrophic failure.	■■	(Vecchiola et al., 2013)
Insurance ■□□	Financial risk sharing strategy, transferring the risk of compensable loss to an insurer.	■□	(Manuj et al., 2008; Tomlin, 2006; Tomlin and Wang, 2011)
Infrastructure Investment ■□□	Building base infrastructures, information technology upgrades and systems integration, and increase degree of automation.	■□	(Chowdhury and Quaddus, 2015; Hendricks and Singhal, 2012)
Inventory Management ■□□	Ordering and stocking decisions, including inventory optimization (e.g. multi-echelon, newsvendor) and inventory investment.	■□	(Tomlin, 2006; Schmitt, 2011; Schmitt and Singh, 2012)
Knowledge Management □□■	Aimed at creating knowledge about business ecosystem's risks and structure (physical and informational) with the capacity to learn from past disruptions to strengthen resilience through improvement of its flexibility, visibility, velocity and collaboration capabilities.	■□	(Ponomarov and Holcomb, 2009; Jüttner and Maklan, 2011)
Mapping ■□□	Macro-graphical representation of the business network and its current state and potential future state. Mapping tools can help companies understand the network in which they are involved and become aware of its vulnerabilities.	■□	(Carvalho et al., 2012; Barroso and Machado, 2011; Briano et al., 2010)
Network Structure Planning ■□■	Deciding on the structure, volume, location, and capacity of interdependent business activities, and processes of the ecosystem, to limit its vulnerability in face of failures through different strategies such as:	■■	(Soni et al., 2014; Carvalho et al., 2012; Zhao et al., 2011; Klibi et al., 2010; Gorgeon, 2015; Schmitt, 2011; Park et al., 2010; Mak and Shen, 2012)
	- Fragmentation, related to decentralization and distribution, namely using different suppliers, different component manufacturers and different location in the production of a good.		*Fragmentation*

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Table 5 (*continued*)

Strategy	Readiness	Response	Recovery	Description	Resilience	Antifragility	References
				- Modularity, to reduce complexity by breaking a complex system into sub-systems with varying degrees of interdependence. - Integration, related to integration, and synchronization of individual functional capabilities such as subsystems, resources, processes, etc. to facilitate agility and flexibility.			(Devendorf et al., 2017) *Modularity* (Hole, 2016a,b) *Integration* (Ponomarov and Holcomb, 2009; Carvalho et al., 2012; Chowdhury and Quaddus, 2015; Hendricks and Singhal, 2012; Glock and Ries, 2013)
Optionality Creation	■	□	□	Availability of options gives the buyer/investor freedom to experiment with uncertainty and benefit from opportunities. E.g. lease rather than buying delivery vehicles enables a company to take advantage of canceling the contract.	□	■	(Taleb, 2012; Derbyshire and Wright, 2014; Russo and Ciancarini, 2017; Gorgeon, 2015)
Postponement	□	■	□	Moving forward operations or activities to the latest possible point in time to recognize and meet demand.	■	□	(Ponomarov and Holcomb, 2009; Tang, 2006; Manuj et al., 2008; Hendricks and Singhal, 2012; Wieland and Wallenburg, 2012; Sodhi and Tang, 2012; Christopher and Holweg, 2011)
Performance Measurement	□	□	■	Attempt to reduce lead times.	■	■	(Ponomarov and Holcomb, 2009; Fang and Sansavini, 2017; Manuj et al., 2008)
Policy Management	■	■	□	Policies, procedures, and guidelines within organizations to mitigate risk and make decisions that lead to resilience/ antifragility-based systems. E.g.: quality assurance practices, human resource policy, optimal inventory policy, ordering policy, strategic risk planning, antifragile guideline principles. - Make-to-order and make-and-buy policies: Make-and-buy enables companies to shift production between in-house producing and outsourcing. Make-to-order is a business manufacturing process where products are not made until customers confirm orders for products.	■	■	(Faisal, 2006; Russo and Ciancarini, 2017; Lichtman et al., 2016; Vecchiola et al., 2013; Natarajarathinam et al., 2009; Chowdhury and Quaddus, 2015; Schmitt, 2011; Devendorf et al., 2017; Tseitlin, 2013; Lengnick-Hall et al., 2011; Zwieback, 2014) *Make-to-order/Make-and buy* (Carvalho et al., 2012; Sodhi and Tang, 2012; Klibi et al., 2010; Tang, 2006; Wieland and Wallenburg, 2012)
Real-time Monitoring	■	■	□	To observe and, if needed, signal an alarm on the external and internal states of the system and its components. It contributes to deeper understanding of how the system operates, namely when it fails, facilitating discovery of the weaknesses. Ex: early warning systems.	■	□	*Warning systems* (Craighead et al., 2007; Becken and Hughey, 2013; Fiksel et al., 2015)
Reengineering	■	□	□	Understanding the business ecosystem structure and reduction of complexity through business process re-engineering initiatives.	■	□	(Ponomarov and Holcomb, 2009; Christopher et al., 2011; Christopher and Holweg, 2011)
Risk Assessment	■	□	□	To interpret and assess the likelihood and severity of events that occur very rarely based on experience.	■	□	(Faisal et al., 2006; Tummala and Schoenherr, 2011; Tomlin and Wang, 2011)
Risk-hedging	■	□	□	Actions aimed at eliminating the exposure to potential catastrophic losses without limiting the potential gains of the system. Hedging involves creating multiple options for decision variables.	■	■	(Jüttner and Maklan, 2011; Klibi et al., 2010; Manuj et al., 2008; Devendorf et al., 2017)
Revision	□	■	■	Considers any substitution and revising the plan of sourcing, operations, and facility (redesign, re-routing, ...) in response to disruptions.	■	□	(Lin and Zhou, 2011; Adhitya et al., 2007; Mak and Shen, 2012;Carvalho et al., 2012; Barroso and Machado, 2011; Tomlin and Wang, 2011)
Sensemaking	□	■	■	Process of creating collective awareness in situations of high complexity or uncertainty in order to anticipate or make decisions. It involves the use of images, etc., to rationalize the experiences with unprecedented and confusing events.	■	■	(Dahlberg, 2015; Jassbi et al., 2015; Lengnick-Hall et al., 2011)
System Analysis/Evaluation	■	□	□	Inspection plans or preventive maintenance programs to ensure that procedures are robust to misestimation of disruption parameters.	■	■	(Pettit et al., 2013; Murino et al., 2011; Soni et al., 2014; Jassbi et al., 2015)
Skin in the Game	■	□	□	Refers to heuristics for all risk-taking emphasizing that decision makers have to be exposed to their decisions' consequences (both downside and upside) and bear the cost of their risky decision making.	□	■	(Taleb, 2012; Gorgeon, 2015)
Supplier Selection	■	□	□	Using different criteria for supplier selection e.g. flexibility, and responsiveness, to increase resilience level of the supplier in face of disruptions.	■	□	(Torabi et al., 2015; Diabat et al., 2012; Glock and Ries, 2013; Ruiz-Torres et al., 2013)

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Table 5 (*continued*)

Strategy Readiness/Response/Recovery	Description	Resilience Antifragility	References
Sourcing ■ ■ □	Planning, designing and building a reliable and competitive supplier base that can be reactive to a shortage. It can include supplier diversification and emergency backup sourcing.	■ □	(Davarzani et al., 2011; Davarzani and Norrman, 2014; Diabat et al., 2012; Christopher and Holweg, 2011; Glock and Ries, 2013; Schmitt and Tomlin, 2012; Mak and Shen, 2012) *Contingent sourcing* (Davarzani et al., 2011; Tomlin, 2006)
Swarming □ ■ □	Swarming as a military tactic implies a convergent attack by many units from all directions simultaneously. Intelligent swarming helps organizations in shifting to a fully networked organization (decentralized and bottom-up) focused on facilitating connections between components, extending the concepts of self-organizing, and self-synchronization by real-time information sharing.	□ ■	(Jones, 2014)
Small-scale Experimentation (Trial and Error) □ ■ □	Running experiments with a "number of small-scale business units to produce different products rather than a single unit producing one product" to test the market. Examples: - Creating Bottom–Up Tinkering: To find unexpected solutions under stressful conditions especially when challenged by "Black Swan" events. - Bricolage: Using diverse range of available resources as inputs into a creative process, allowing organizations to evolve from the bottom-up through intimate knowledge of resources, observation and listening, trusting one's ideas, self-correcting structures, consideration of feedback, etc.	□ ■	(Taleb, 2012; Derbyshire and Wright, 2014) *Tinkering* (Taleb, 2012; Danchin et al., 2011; Hole, 2016a) *Bricolage* (Taleb, 2012; Derbyshire and Wright, 2014)
Via Negativa ■ □ □	Via negativa is a subtractive strategy by removing what is potentially harmful or unnecessary to the process, i.e. a recipe for cutting off everything that's not of importance.	□ ■	(Taleb, 2012)
Weak links □ ■ □	To quickly detect a fault condition and break a "weak link" stop propagating failures.	■ □	(Hole, 2016a; Hole, 2016b)

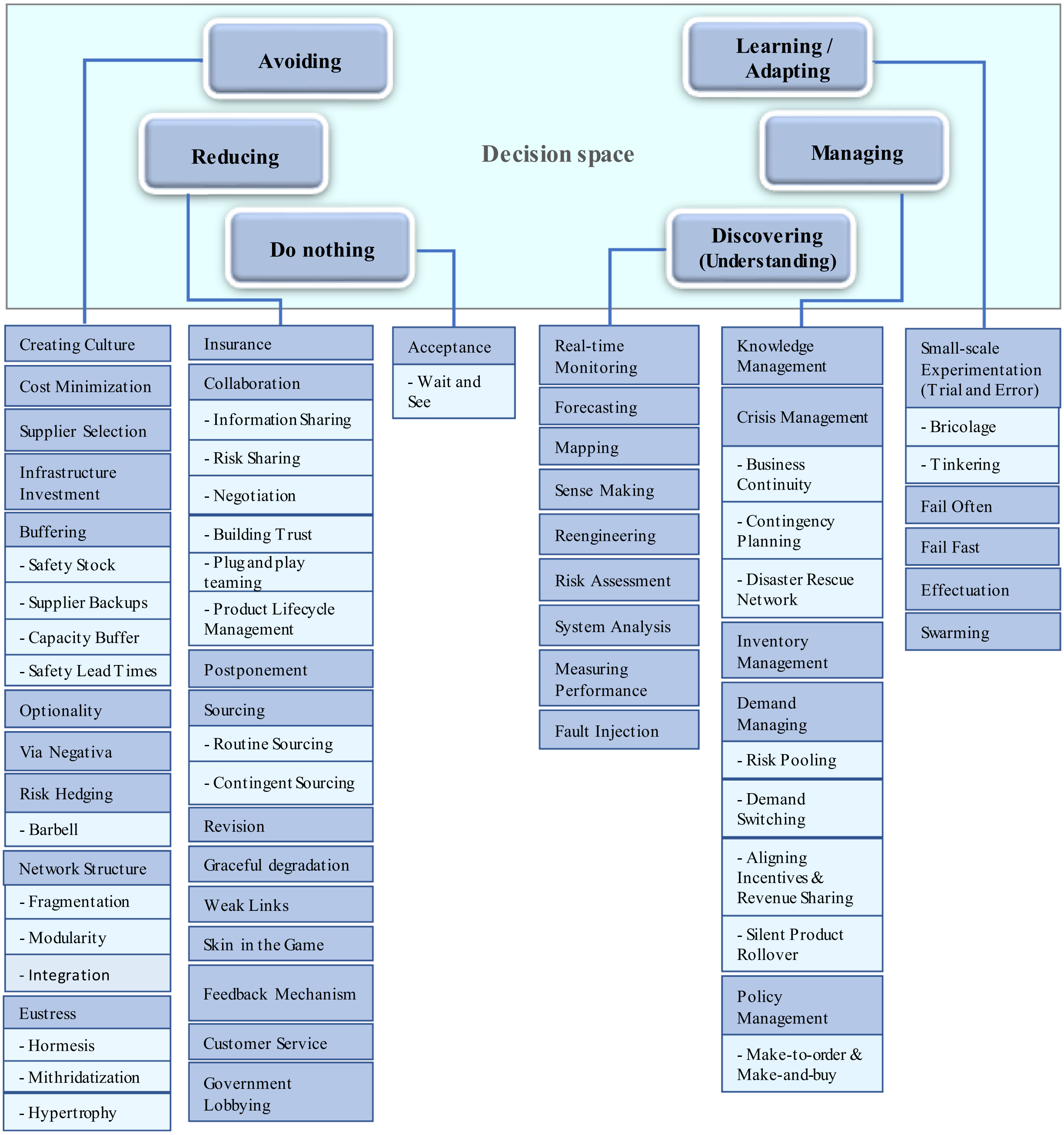

Fig. 3. An overview of disruptions coping strategies.

case of disruption in the primary engine. In Lengnick-Hall et al. (2011) some attributes of organization's resilience are highlighted such as flexibility, agility, and adaptability. Similarly, (Carvalho et al. (2012) suggests that the term resilience has the following attributes: diversity, adaptability, and cohesion. Also (Jüttner and Maklan, 2011) identifies four capabilities of resilience, as the most frequently mentioned in the literature, like flexibility, velocity, visibility, and collaboration. According to these authors, such capabilities can support and secure the efficient and effective business readiness, response and recovery against disruptions.

An extensive list of capabilities found in literature is presented in Table 4. This compilation provides a portfolio of capabilities that, according to the literature, can be activated to provide resilience and/or antifragility properties to the business ecosystem with. This table can, therefore, be used as a guide for individuals, teams, and organizations to deal with disruption, and consequently help in decision making under uncertainty to survive and even gain and grow from disruption relying on these capabilities. The boxes in the Resilience / Antifragility column of Table 6 are filled in according to the authors' perception from the analyzed literature.

These capabilities are the elements that strategies can activate in response to disruptions.

4.2. Contributing knowledge areas

In this section, we analyze the literature with the aim of answering the following research question: Which knowledge areas are contributing to "Resilience" and "Antifragility"? The knowledge underpinnings of these concepts in disruptive business ecosystems and their organizations are related to different concepts drawn from various disciplines such as collaborative networks, systems thinking, thermodynamics, social sciences, biology, management science, and ICT. We

Table 6
Capabilities.

Capabilities	Description	Resilience	Antifragility	References
Agility	Ability to rapidly respond to unexpected / unplanned for external circumstances.	■	□	(Faisal et al., 2006; Carvalho et al., 2012; Ponomarov and Holcomb, 2009; Soni et al., 2014; Camarinha-Matos, 2014; Zitzmann, 2014; Briano et al., 2010; Christopher et al., 2011; Wieland and Wallenburg, 2012)
Adaptability	Ability to modify operations in response to disruptions. E.g. Re-routing and substituting requirements, seizing advantage from disruptions, alternative technology development, and learning from experience.	■	■	(Bhamra et al., 2011; Ponomarov and Holcomb, 2009; Soni et al., 2014; Russo and Ciancarini, 2017; Lichtman et al., 2016; Madni and Jackson, 2009; Carvalho et al., 2012; Jones, 2014; Fiksel et al., 2015; Jassbi et al., 2015; Christopher and Holweg, 2011; Adhitya et al., 2007; Bakhouya and Gaber, 2014)
Cohesiveness	Presence of unifying forces or bonds that preserve systems' continuity such as: Strong corporate or brand identity; employee's pride, loyalty and teamwork; strategic partnerships with suppliers; strong values and principles; visionary leadership.	■	■	(Pettit et al., 2013; Gotham and Campanella, 2010)
Convexity	A much-debated property in quantitative finance and risk management, sometimes used as synonymous of antifragility, representing systems with positive asymmetry in which "potential losses are limited and typically known beforehand while potential gains are immense and unknowable," thus usually leading to exponentially more benefit as randomness increases.	■	□	(Derbyshire and Wright, 2014; Hespanhol, 2017; Russo and Ciancarini, 2017)
Cognitive ability	Capacity of acquiring knowledge and understanding through experience.	□	■	(Russo and Ciancarini, 2017; Lichtman et al., 2016; Jones, 2014)
Creativity & imaginative capacity	Improvisation, creativity, and imaginative capacity as enablers for opportunity identification in the event of a disaster.	□	■	(Gotham and Campanella, 2010; Dahlberg, 2015; Hespanhol, 2017)
Diversity	Existence of multiple talents and work styles that enable innovation in response to changing conditions." Diversity involves offering alternatives so that even when challenges impact a particular alternative, others can prevent degradation from normal operation.	■	■	(Bhamra et al., 2011; Gotham and Campanella, 2010; Carvalho et al., 2012; Frankenberger et al., 2013; Tomlin and Wang, 2011; Schmitt and Tomlin, 2012; Hole, 2016a; Mak and Shen, 2012)
Dispersion	Broad distribution or decentralization of assets, including key resources and markets.	■	□	(Pettit et al., 2013; Fiksel et al., 2015; Christopher and Holweg, 2011)
Efficiency	Ability to produce outputs with minimum resource requirements. Companies with this capability can adjust better than others to for instance, unexpected shortages of raw materials or energy.	■	□	(Pettit et al., 2013; Bhamra et al., 2011; Chowdhury and Quaddus, 2015; Fiksel et al., 2015)
Evolvability	Ability of a system to refine its structure or function to adapt to changing circumstances, improving future behavior, generate novelty and innovate in response to disruptions.	■	□	(Minami et al., 2014)
Elasticity	Capacity of restoring a system to a stable state following a disturbance. It is indicated by the degree of flexibility, redundancy, and persistence of critical characteristics, resources, and functions that can be deployed when under stress. Sometimes used as a synonymous of resilience.	■	■	(Chroust and Aumayr, 2017; Ponomarov and Holcomb, 2009; Etingoff, 2016)
Flexibility	Ability to quickly change inputs or mode of delivering outputs to ensure that changes caused by the disrupted event can be handled flexibly by the organization. E.g.: flexible transportations systems, production facilities, supply base, capacity, supply contract, and manufacturing process.	■	■	(Pettit et al., 2013; Carvalho et al., 2012; Sodhi and Tang, 2012; Danchin et al., 2011; Manuj et al., 2008; Christopher et al., 2011; Hendricks and Singhal, 2012; Christopher and Holweg, 2011)
Financial strength	Capacity to absorb fluctuations in cash flow. E.g.: insurance, funds availability, profitability, portfolio diversification, price margins.	■	□	(Pettit et al., 2013; Chowdhury and Quaddus, 2015; Fiksel et al., 2015; Tomlin and Wang, 2011)
Fault tolerance	Enabling a system to "absorb changes of state variables, driving variables, and parameters, and" continue to function.	■	■	(Chroust and Aumayr, 2017; Chroust and Aumayr, 2017; Monperrus, 2017; Russo and Ciancarini, 2017; Tseitlin, 2013)
Hysteresis	A characteristic of complex systems relating to an irreversibility or persistence of the effects of an event (shock) in future (delayed effect), after disappearance of the factors that caused that event. Even if the system returns to its original configuration, it takes a different path due to endogenous structural changes.	□	■	(Devendorf et al., 2017)
Market Position	Positioning a company or its products in specific markets, including: Product differentiation, market share, brand equity, customer loyalty/retention, customer relationships, etc.	■	□	(Pettit et al., 2013; Soni et al., 2014; Chowdhury and Quaddus, 2015; Fiksel et al., 2015)
Observability	Ability to observe and, optionally, signal alarms on the external and internal states of the system and its components.	■	□	(Tseitlin, 2013)
Organizational capability	Human resource structures, policies, skills, and culture, including creative problem-solving culture, accountability, diversity of skills and experience, Cross-training, benchmarking, and feedback mechanisms.	■	■	(Jaaron and Backhouse, 2014; Fiksel et al., 2015; Lengnick-Hall et al., 2011; Tseitlin, 2013)

(*continued on next page*)

Table 6 (*continued*)

Capabilities	Description	Resilience Antifragility	References
Redundancy	Having multiple assets to perform the same function, including safety stocks, extra inventory, over capacity, multiple sourcing, and backup suppliers.	■ ■	(Carvalho et al., 2012; Ponomarov and Holcomb, 2009; Derbyshire and Wright, 2014; Jüttner and Maklan, 2011; Madni and Jackson, 2009; Carvalho et al., 2012; Barroso and Machado, 2011; Tang, 2006; Danchin et al., 2011; Diabat et al., 2012; Tomlin and Wang, 2011; Glock and Ries, 2013; Tseitlin, 2013)
Resistance	Ability of a business ecosystem to resist shocks/stress without changing its initial configuration.	■ □	(Murino et al., 2011; Wieland and Wallenburg, 2012)
Simplicity	A way to apprehend the complexity and uncertainty by subtraction of unnecessary elements, including removal of harmful elements or entities.	□ ■	(Taleb, 2012; Gorgeon, 2015)
Sustainability	The process of enduring and maintaining change, meeting the needs of today without compromising the future.	■ □	(Murino et al., 2011; Ponomarov and Holcomb, 2009; Soni et al., 2014; Camarinha-Matos, 2014; Minami et al., 2014)
Security compliance	Capability to defend against (cyber, equipment and personnel) attacks.	■ ■	(Pettit et al., 2013; Murino et al., 2011; Faisal et al., 2006; Soni et al., 2014; Chowdhury and Quaddus, 2015; Manuj et al., 2008; Fiksel et al., 2015)
Self-* properties	Refer to attributes of systems that can automatically control, maintain or manage themselves throughout different disruptive/volatile scenarios. Including: - Self-organizing: Property that emerges from inside the system (not being controlled by any external entity) and causes overall order arises from the initially disordered system. - Self-healing: Ability to detect abnormalities and take corrective actions. - Self-adaptation: Ability to automatically (i.e., with less or no interference) adjust parameters in response to changes in the environment (through introspection or self-maintained models). - Self-management: Ability of a system to reconfigure itself in response to external changes without human intervention but complying with high-level management policies.	■ ■	(Monperrus, 2017; Russo and Ciancarini, 2017; Madni and Jackson, 2009; Frankenberger et al., 2013; Jones, 2014; Danchin et al., 2011; Abid et al., 2014; Lengnick-Hall et al., 2011; Ibryam, 2016)
Transformability	Ability of a system to fundamentally transform / recreate its structure, processes and behavior in order to deal with current hazards as well as similar ones it might face in future.	■ ■	(Gotham and Campanella, 2010)
Visibility	Awareness of the status of operating assets (orders, inventory, transportation, and distribution) and the of environment of the business ecosystem.	■ ■	(Pettit et al., 2013; Ponomarov and Holcomb, 2009; Soni et al., 2014; Jüttner and Maklan, 2011; Hendricks and Singhal, 2012)

further detail the main contribution of these disciplines below.

Collaborative networks. The area of collaborative networks is, in fact, a recent discipline that has emerged from interdisciplinary contributions of various other areas including computer science, industrial engineering, sociology, management, etc., and focuses on the structure, behavior, and evolving dynamics of networks of autonomous entities that collaborate to better achieve common or compatible goals. In the particular case of business ecosystems, a kind of long-term strategic collaborative network, visibility (e.g. organization's willingness to share even sensitive risk and risk event-related information) can be increased which can help firms to adjust to disruptions quickly (Graça and Camarinha-Matos, 2017; Soni et al., 2014; Camarinha-Matos, 2014). Collaboration inside the ecosystem provides an aggregating factor for building resilience and antifragility (Camarinha-Matos, 2014; Berkes, 2017), namely by:

- Providing a survival capability and sustainability through collaboration, negotiation, and joint problem solving.
- Identifying new ideas and growth opportunities by increasing direct communication and enhancing the business acumen to deal with emergent problems through collaborative innovation and collaborative problem solving.
- Facilitating knowledge sharing and building a culture of trust, a requirement for dealing with unreliable information sources.

Furthermore, new perspectives of collaboration are brought in recently, which are important components of resilience and antifragility-based systems:

- Collective awareness and collective intelligence: Collective awareness refers to a common and shared understanding inside groups and communities to coordinate members activities and behaviors through communication. In business ecosystems, it also relates to supporting environmental awareness, to achieve changes in lifestyle of customers, production, and consumption patterns to better cope with volatile business environments and taking sustainability-oriented decisions. Collective intelligence requires a form of collective awareness that emerges as a result of collaboration and competition for promoting innovation in a business ecosystem (Russo and Ciancarini, 2017).
- Knowledge co-production: referring to the collaborative process of bringing diverse research, practice, and policy actors together to combine various knowledge sources and types, to address a problem and generate new knowledge. It may involve participatory research/learning together and co-creation processes to identify new ideas and growth opportunities (Berkes, 2017).
- Collaborative adaptive management: An approach towards "adaptive governance" (in the sense of flexible and learning-based collaborations and decision-making processes) that combines knowledge and experience of multiple actors to respond to conditions in which uncertainty is high (Berkes, 2017).

Systems thinking. This area offers a holistic approach to problem-solving that attempts to view systems from a broad perspective rather than focusing only on specific events in the system. It means zooming out to get the broadest possible view of a situation to design more impactful solutions. This view is particularly useful to identify and address complex problem situations to better predict their complex behaviors.

Business ecosystems, which are influenced by and interact with the complex and volatile surrounding environment, typically try to build resilience or antifragility to survive or grow through enacting adaptive and self-* capabilities. With the emergence of self-* mechanisms, feedback processes become more complicated and need to be supplemented by systems thinking tools to allow a deeper understanding of the underlying system. This is reflected in the following ways (Chroust et al., 2016):

- Understand the relationships, interactions, and critical connections among components of the disrupted system to improve the reaction to a disruption.
- Understand the dynamic, nonlinear, fuzzy, and complex system behavior.
- Follow the chain of events occurring in all phases of a disruption.
- Provide in-depth systematic investigation of the system's vulnerability and resilience and predict the impact of a disruption to the system.
- Discover and represent feedback processes to underline observed patterns of system behavior and analyze self-* mechanisms.

As such, systems thinking has contributed a variety of principles and tools for analyzing and changing systems. Relevant inputs from this area include:

- System dynamics: promising approach to model risk information flows and "understand the nonlinear behavior of complex systems over time using stocks, flows, internal feedback loops, and time delays" (Bakhouya and Gaber, 2014).
- Systems engineering: a collaborative approach that uses systems thinking principles and tools including modeling and simulation, to design and manage complex systems and respond to both disturbances and opportunities (Verhulst, 2014).
- Complexity theory: providing an appropriate language, metaphors, and tools to examine how systems adapt and cope with conditions of uncertainty. It shows that by bringing organizations to the edge of chaos, self-organization will emerge (a core of antifragility) (Dahlberg, 2015; Gorgeon, 2015).
- Chaos theory: a useful conceptual framework to study nonlinear dynamic systems, that are highly sensitive to initial conditions, namely how business ecosystems adapt and cope with situations of uncertainty (Gómez-Uranga and Etxebarria, 2015).
- Scenario planning: a strategic decision-making method to make flexible long-term plans. Through scenario planning organizations can recognize and show how multiple factors and their causal relationships may combine in different ways to create surprising futures. Therefore it allows organizations to be prepared to meet these challenges (Derbyshire and Wright, 2014).

Thermodynamics. A branch of physics concerned with heat, temperature and their relation to energy. Particularly important here is the second law, which addresses entropy as a move from order to chaos. Over time, similarly in business, a useful order decays into non-useful order (growth of entropy).

In mechanical and other systems that linearly follow physical laws, the decay is mostly inevitable, and irreversible. However, complex, chaotic, and other non-linear systems can overcome and recover from degradation tendencies, which contradicts the principle of permanent growth of entropy. This is based on the idea that energy and material are exchanged with the external world in open systems and when systems move away from equilibrium, they can move from one stable stage to another. This relates to the new meaning of the second law (Gómez-Uranga and Etxebarria, 2015), according to which each entity learns and remembers how to leverage opportunities for reverse-entropy. Accordingly, complex adaptive systems are open, complex, and act far from equilibrium, where entropy may decrease. This is due to self-organization which can happen after enough degree of complexity is achieved (Gómez-Uranga and Etxebarria, 2015). Paradoxically, resilience and antifragility in business ecosystems require some elements that face and even embrace desirable variance when confronting disruptions. At the same time, stability and limiting undesirable variation are requirements for long-term sustainability of the network (Taleb, 2012). Because of these two conflicting perspectives, various works seek equilibrium across both stability and evolvability, certainty and uncertainty. This inspired some authors to bring methodological tools of thermodynamics in these areas to better explain the evolution of complex adaptive systems (Gómez-Uranga and Etxebarria, 2015). Examples:

- Phase transition: describing the transformation of a thermodynamic system from one phase to another by heat transfer. Analogously, phase transitions in complex systems imply a transition from order to chaos that happens in the edge of chaos. Therefore, it is essential to determine the system behavior in the vicinity of critical points to analyze the phase transition. An example is achievement of resilience control in large-scale networks when a control parameter reaches critical value (Dahlberg, 2015; Chikumbo and Norris, 2015).
- Multi-equilibria: which considers the possibility of more than one outcome or state of equilibrium in which a disturbed system can re-emerge after a shock. In "multi-equilibria resilience, the focus is on how far a system can remain in a particular state before reaching" a critical threshold and moving to a new state ("regime shifts") (Etingoff, 2016).
- Path-dependence: a notion related to "hysteresis" that implies the current state of a system is dependent on its previous states. Path-dependence and its associated fundamental notions, such as positive feedback-loops and irreversible processes are at the heart of the evolutionary approach. Prediction of future states of a complex system is complicated because the result does not depend on the current state, but also along the way of its evolutionary history, which forms the basis for the heuristics and adaptability based on resilience and antifragility (Dahlberg, 2015). Since antifragility is path dependent, an attack may result in different responses in various occasions (Devendorf et al., 2017).

Social sciences. This area comprises a number of disciplines concerned with society and the relationships among individuals within a society. It includes various branches, such as anthropology, economy, geography, history, political science, psychology, social studies, and sociology.

Resilience and antifragility are explored within these disciplines in three primary branches: sociology, psychology, and economics. In sociology, resilience and antifragility describe the behavioral response of social systems (communities, organizations, and economies) to disruptions, which is determined by the degree of "spontaneous order" (self-organization), learnability, and adaptive capacity of systems in face of stresses and disturbances (Ponomarov and Holcomb, 2009). Furthermore social systems with their collective memory and experiences promote resilience and antifragility by developing creativity and innovations to deal with disruptions and surprises (Lorenz, 2013). A psychological perspective on resilience and antifragility has its roots in developmental theories that describe human growth and change over the life cycle, encompassing an understanding of biopsychological factors (Ponomarov and Holcomb, 2009). From the economics area, recent reports on investments or trading options in the financial markets point to many different trends and strategies that enable firms to avoid maximum potential losses (resilience) or grow in face of catastrophes (antifragility) (Taleb, 2012). Some relevant ideas include:

- Creative destruction or theory of economic innovation - process of incessantly revolutionizing the economic structure from within (destroying the old and creating a new one) as a result of industrial mutation (Lorenz, 2013).
- Deutero-learning or learning how to learn - process of collaborative inquiry and reflection to facilitate learning at the organization (Lorenz, 2013).
- Developmental psychopathology, to examine what makes some people more resilient than others (Ponomarov and Holcomb, 2009).
- Post-traumatic growth or benefit finding, the positive change experienced because of adversity, rising to higher levels of functioning (Taleb, 2012).
- Mindfulness engineering, an approach that integrates the concept of mindfulness with the resilience and sustainability of the systems. It emphasizes human characteristics such as adaptation, cognition, and learning capabilities in shaping systems' resilience and antifragility capabilities such as thriving in the face of disruptions (Beigi, 2014).
- Dual process theory (two systems metaphor), applied to decision making in the disruptive environments (Kahneman, 2011).
- Growth mindset versus "fixed mindset," which refers to people that believe each failure is an opportunity to learn (Pink, 2011).
- Venture capital (VC), is financing that investors provide to startup companies knowing that most of these emerging businesses will fail, but a few will succeed to the extent that the benefit will be far higher than the losses incurred in failed ventures. VC learns from unsuccessful investments to make smarter investments in the future (Mougayar, 2013).

Biology. This is a discipline that studies life and living organisms including their structure, function, interaction, distribution, growth, origin, development, and evolution. Its contribution to resilience and antifragility is related to some characteristics of natural systems to creatively respond to changes (novelty creation) in their environment. For example, "some neural systems exploit phase transitions as a source of novelty and flexibility which allows them to continually adapt to stimuli" (Chikumbo and Norris, 2015). Another example of antifragility in nature is the gene-centered view of evolution, whereas adaptive evolution occurs through the differential survival of competing genes. While individual organisms are relatively fragile, the genes benefit from shocks and enhance their fitness by transferring information to other units (Taleb, 2012). This area has also inspired buffering, hypertrophy, and hormesis strategies to cope with disruption (Taleb, 2012). Other examples:

- Natural selection-driven evolution, survival of the fittest, not strongest, is a process in which organisms are possessing specific genotypic characteristics that make them better adjusted to an unstable environment and allow them to choose from alternatives that enhance their chance to survive and reproduce (Tseitlin, 2013). This is an obvious example of responding to disruptions creatively (Danchin et al., 2011).
- Biomimicry, using designs inspired or copied from nature to solve complex problems. The purpose is to emulate nature's time-tested models, and strategies to create products, processes, and policies that enable a system to adapt quickly when disruptions happen (Camarinha-Matos and Afsarmanesh, 2018).
- Degeneracy/functional redundancy, the process of increasingly deteriorating over time, which is the nature of living systems - *"physical death is a necessary part of these systems because it gives birth to new life and a renewal of function"*(Taleb, 2012).
- Epigenetic, a particular field in biology, related to the concepts of evolution, learning, and adaptation in nature, which involves changes that affect gene activity (expression) without modifying the genotype itself. It shows how flexibility and tinkering of the genome enable it to adapt to the changing environment (Danchin et al., 2011).

Management sciences. This discipline covers the application of methods to solve problems and decision making in organizations, with strong relation to business, engineering, and other sciences.

Uncertainty is a defining characteristic of managerial and organizational decision making. Essential aspects of resilience and antifragility such as flexibility, maintenance, adaptability, recovery, and transformability are addressed. Another important issue is dealing with the outcomes of resilience stress considering that resilience is a distinct source of sustainable competitive advantage (Ponomarov and Holcomb, 2009). Furthermore, focusing on building highly effective systems to detect and correct errors and learn from them is an essential organizational element to become a learning and antifragile organization by regenerating itself in a volatile environment (Jaaron and Backhouse, 2014; Tseitlin, 2013). Therefore, aspects such as transformation, adaptive capacity, dynamic partnerships, and inter-organizational linkages are considered to decrease the likelihood of failures. Some relevant ideas, include:

- Adaptive cycles, also called "panarchy", which encapsulate the "notion that complex systems are not static, and change through a cycle of growth, accumulation, destruction, and renewal" (Chikumbo and Norris, 2015). The focus is on processes of destruction and reorganization. These cycles are often neglected in favor of growth and conservation which alternates between the slow phase of growth and conservation and a rapid phase of reorganization that creates opportunities for innovation.
- Y-management, which assume that employees are self-motivated and able to learn how to solve problems themselves (tinkerers). Organizations that employ Y-management techniques hire people with 'growth mindset' who will thrive in this environment (Pink, 2011).
- Holacracy, a theory that emphasizes the importance of distributing authority and decision-making (decentralized management) to individuals and teams in organizations because of their self-organizing ability (psychological, physical and social) in ever increasing complexity (Kapalko, 2018).
- Heuristic based decision making and "convex heuristics", which are simplified decision-making rules from risk management and antifragility metaphor (Taleb, 2012).
- Learning-by-doing, a process to learn during the practical experience which is towards adaptive governance (manage and learn) transforming experience into knowledge and moves learners towards new knowledge and more profound understanding (Berkes, 2017).

ICT. Information and communication technology (ICT) can be used as an important enabler for resilience/antifragility by:

- Reinforcing the socialization capability, both during awareness formation and self-adaptation phases to cope with disruption.
- Developing mechanisms to reach significant levels of collective awareness of disturbances in the environment, through improved information management (collecting, analyzing, sharing, and disseminating information to the right agents at the right moment) during a disruptive episode.

- Supporting learning from experiences using tools such as machine learning.

In fact, various types of ICT tools have been developed for the activities required in the various phases of a disruption. On the other hand, ICT itself is vulnerable to disasters (Chroust and Aumayr, 2017). Therefore, another focus is on architecting and designing approaches that support building systems that have the potential to embrace stressors (Chikumbo and Norris, 2015). Indeed, there are tools, platforms, architectural styles, and methodologies that help creating ICT systems with resilience/antifragility characteristics as illustrated in the following two directions:

1 Facilitator of resilience/antifragility in business ecosystems:
  - Distributed ICT systems, which are ecosystems of autonomous entities interacting with each other and environment (Hole, 2016b).
  - Microservices, as a way for architecting applications which offer a great degree of flexibility while the whole system is continuously evolving. Microservices provide flexible structures with benefits of weak links, redundancy, modularity, diversity, and scalability that can significantly limit the vulnerability of systems. It is also easier to test, upgrade, and replace old services with new ones (Russo and Ciancarini, 2017; Hole, 2016a; Hole, 2016b).
  - Blockchain, a secure distributed storage that is typically managed by a peer-to-peer network supporting the transmission of digital assets. Blockchain uses securely encrypted identification methods having a consensus mechanism which resists attacks. Combining blockchain with machine learning algorithms would cause systems to improve continually, providing better response to disruptions in the future and perhaps even predict potential failures (González et al., 2017).
  - Cloud computing provides both highly redundant computing, and data storage enabling diversity to facilitate antifragility against system downtime (Abid et al., 2014; Hole, 2016b).
  - Evolutionary computation, a family of problem-solving algorithms inspired by biological evolution, involving methods and techniques that are continually evolving and optimizing, such as genetic algorithms. Genetic algorithms, allow creating “digital organisms” that are expected to evolve and capable of self-organizing and self-adapting to changes in their surrounding environment (Kapalko, 2018).
  - Multiagent-based modeling, an approach to bring intelligent autonomous and distributed solutions and test their effectiveness in the context of disaster response (Minami et al., 2014).
  - Chaos engineering, a new approach for experimenting on distributed systems to create antifragility by evolving systems to survive the chaos. It involves injecting failures to systems so that they be prepared for future disasters. Chaos engineering, by forcing human feedback, makes the social-technical system antifragile and not only the software system (Ibryam, 2016).
  - DevOps, a modern organizational philosophy focused on tools and techniques to integrate the development (Dev), quality assurance, and operations (Ops) departments. When applied to ICT development, DevOps can be considered an antifragile methodology aimed at aligning entire organizations toward common goals to improve the antifragility of complex systems. It is an example of “skin in the game” such that a team that handles both development and operations has something to lose in a given crisis (Russo and Ciancarini, 2017; Zwieback, 2014; Ibryam, 2016).

2 ***To make the ICT systems more resilient/antifragile:***

This includes developing both resilient/antifragile products and processes. Examples:

- Product:
  - Auto-scaling feature allows applications to automatically adjust computing resources depending upon actual usage. When traffic increases, auto-scaling can handle the extra load by creating more instances of the application or removing instances in case of decreased demand. Such system is antifragile because there is gain from increased traffic (stress) and system becoming able to handle pressure better (Ibryam, 2016; Kapalko, 2018).
  - Automatic bug detection and repair, software that fixes own bugs (self-healing) using techniques that automatically change the code at runtime in response to errors (Monperrus, 2017), an example of resiliency (Ibryam, 2016). These systems are self-aware and if they learn from bugs, then they can be considered antifragile (Monperrus, 2017; Russo and Ciancarini, 2017).
  - Adaptive fault tolerance, when a software system exposed to faults continuously improves its tolerance by learning from errors (Monperrus, 2017; Russo and Ciancarini, 2017).
  - Fault injection in production, a method of fault injection during business-critical operations in the field, with real scale, real inputs, real users (Monperrus, 2017). A software system produced in this way “is antifragile since it decreases the risk of miss, mismatch, and rot of error-handling code by continuously exercising it” (Monperrus, 2017; Russo and Ciancarini, 2017).
  - Failure-as-a-Service (FaaS) allows cloud services to perform large-scale, online failure in real deployments routinely. As a failure testing solution, it supports fast recognition when something is not working and provides visualization, rapid prototyping, agile development and other fast fail methods that help organizations iterate new ideas for greater success. “Gremlin” is an example of such framework (Kapalko, 2018).
- **Process:**
  - Continuous deployment, a process with four sub-dimensions (deploy to production, verify the solution, monitor for problems, and respond and recover) through which features, and bug fixes are continuously released in production environment. It creates “continuous partial system failures and forces organizations to react to stress faster through strategies such as redundancy, rolling upgrades, rollbacks, and avoiding single points of failure”. With continuous deployment, errors have smaller impacts. “When an error is found in production, the new version can be released very quickly” since the process supports very quick verification and deployment phases (Monperrus, 2017; Ibryam, 2016).
  - Test driven development, a process for writing automated tests for each feature that relies on the repetition of a very short development cycle. It allows continuous deployment (short release cycle) using “test-first” development and the trust given by the automated tests in order to prove functional code to meet the requirement (Russo and Ciancarini, 2017).
  - Iterative development, a method that divides a project into many releases through iterative cycles, allowing software developers to take advantage of what was learned during use/development of earlier parts/versions of the system (Ibryam, 2016).

A general overview of these contributions is shown in Fig. 4.

4.3. Representative examples

To illustrate resilience and antifragility cases and approaches, this section includes several representative examples from different sectors.

4.3.1. Overview

The mythical Phoenix, an immortal bird that dies by fire and rises from the ashes in the same state, is resilient. The Greek mythological creature Hydra that grew two new heads every time one was removed (the disruptive event) is an ultimate metaphor of antifragility (Taleb, 2012; Benson, 2013). It is interesting to look for real-life versions of Phoenix and, Hydra as illustrated bellow:

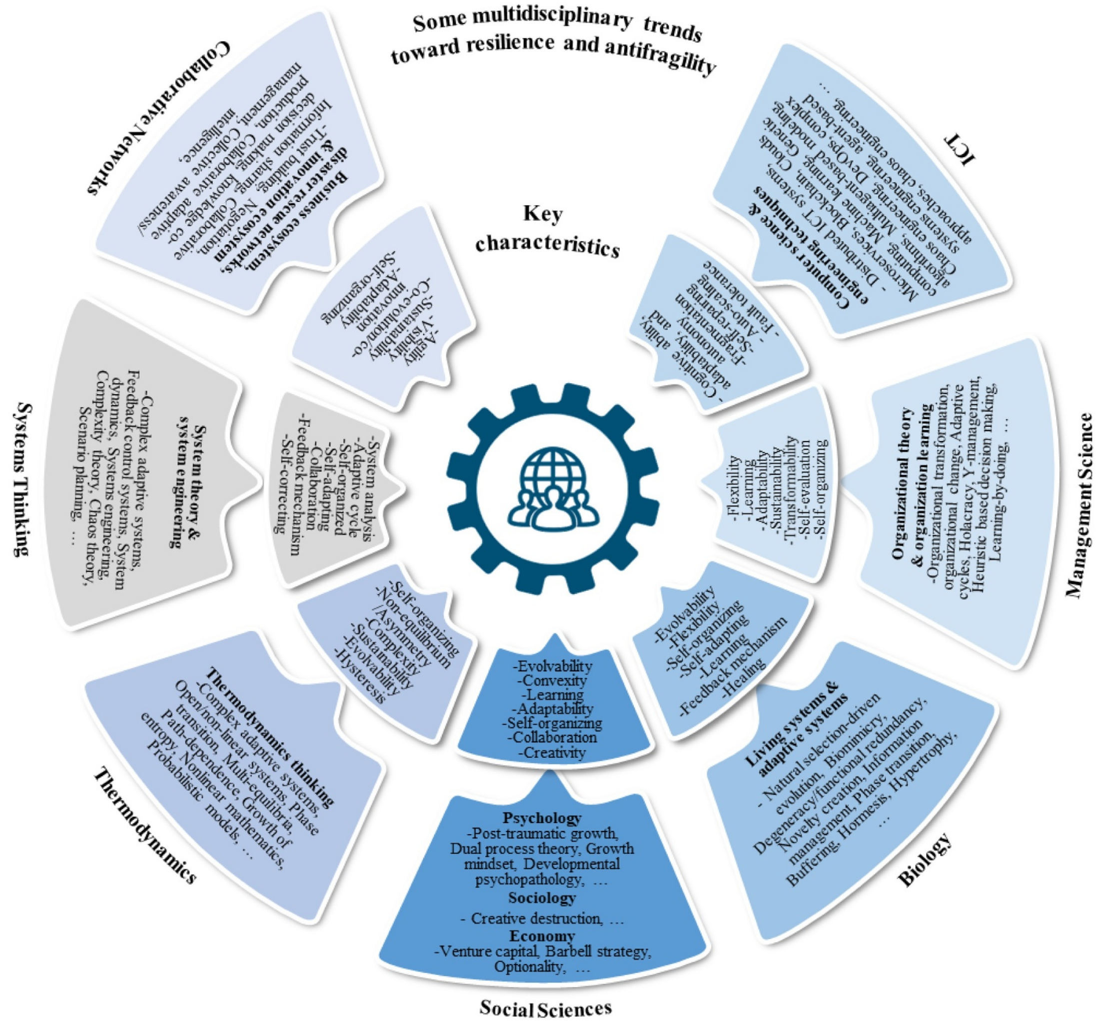

Fig. 4. Contributing knowledge areas.

***Nature*.** The human body is a good example of antifragility. Our body evolves through failures becoming adaptive to operate during stress and chaos. Muscles get stronger when stressed with weight or physical exercise. The immune system requires constant pressure from microbes to stay reactive (Monperrus, 2017), adapt and self-repair, strengthening when exposed to germs and vaccination (Taleb, 2012). Moreover, nature accepts a short-term loss for a long-term gain. Forest fires, for example, destroy trees, but they also enable trees and other desirable vegetation to flourish. Periodic small fires make the forest antifragile by removing the most flammable material, so that the fire does not have the opportunity to grow stronger and cause more damage (Taleb, 2012).

***History*.** Almost everything in the world that has lasted for a long time has an antifragile system in place. The life expectancy of some types of things increase as they survive longer as Nietzche says "that which doesn't kill us make us stronger" which when applied to business is called "Lindy effect": "the longer a business has been around, the more likely it will survive in the future" (Benson, 2013). Likewise, being banned may help books become antifragile (regarding longevity and popularity) as 46 of the 20th century's top 100 novels were targets of ban attempts (Taleb, 2012; Zwieback, 2014). Similarly, technology mortality decreases with time (Kapalko, 2018). Many cities could survive for sometimes more than five thousand years through floods, wars, and even atomic bombs on them, as they are continuously adapting complex networks that are incredibly resilient. A city thrives as it grows in size by enabling decentralized, adaptation to changes, and resilient access to information. Corporations, on the other hand mostly stop growing because of their hierarchical structure and centralized management (Taleb, 2012).

History is filled with cases showing that failure is often beneficial in growth, learning, transformative resilience, and achieving success. Some examples:

- Individuals
  - Steve Jobs; at the age of 30, was greatly successful, fabulously wealthy and a global celebrity. And then it all came crashing down. But he had a fantastic comeback, as he said in his speech to Stanford graduates: *"Fired from Apple was the best thing that could have ever happened to me. It freed me to enter into one of the most creative periods of my life. It was awful tasting medicine, but I guess the patient needed it* (Marston and Marston, 2018)*."*
  - Tomas Edison, one of the first American entrepreneurs is a particularly inspiring historical example of the idea of failing forward, as reflected in his famous sentence when a massive fire erupted in his laboratory: "*There is great value in disaster. All our mistakes are burned up. Thank God we can start anew.*" (Marston and Marston, 2018).
- *Organizations*
  - Mölnlycke AB; a large textile company in Boras, which in reaction to the crisis in the Swedish textile industry sold its home textiles units and changed its focus to healthcare products made from cellulose fibres instead of textile products made from cotton. By

Table 7
Engineered examples of resilience and antifragility

Example	Description	References
Resilience R Antifragility A		
Netflix A R	**Purpose:** on-demand media service provider and a pioneer in the area of antifragile internet-based systems. **How:** Applying the "simian army," a suite of software tools referred to as "monkey services," that routinely generate real system failures intending to use lessons learned to prevent more massive disruptions. They create an expectation of the failure occurrence and constant re-creation. When the re-creation process can go beyond merely rebuilding what was existed before, the system shows antifragility, and when it only bounces back to the previous state, the system shows resilience. **Covered strategies/capabilities:** - **Fault injection**: Introducing small amounts of stress to build resistance against future stressors. - **Fail fast:** E.g., the "Chaos Monkey" tool randomly crashes some production servers, the "Latency Monkey" introduces random latencies in the server network, and the "Chaos Gorilla" causes an entire failure by simulating two failure modes (network partition and total zone failure). - **Modularity:** Exploiting microservices architecture, with the benefit of flexibility and diversity. - **Redundancy:** Through a cloud infrastructure. - **Weak links**: Using circuit breakers prevent failure propagation to other services. - **Other:** Fault tolerance and isolation, Fallbacks and graceful degradation, Auto-scaling.	(Monperrus, 2017; Devendorf at al., 2017; Abid et al., 2014; Hole, 2016a)
Etsy A	**Purpose:** E-commerce website focused on handmade and unique manufactured items. **How:** Focusing on the idea of "JUST DO IT" which often means embracing failure. The idea is to make many small changes frequently and deploy them. This culture enables Etsy to learn and improve (build and release robust features while serving over billion-page views per month) from failures. **Covered strategies/capabilities:** - **Fault injection**: Intentional fault injection to handle failures and learn to recover quickly. - **Continuous deployment**. Continuous deployment at Etsy means running all tests, all the time. The point is that "continuous deployment" is real and they make small changes frequently and do deploys. - **Fallback and graceful degradation**: Quickly going back to a previously working version should the newly deployed one be found defective. - **Skin in the Game / DevOps**. - **Collaboration:** Through a culture of transparency, monitoring, speed, informed risk-taking, automated testing, error log analysis, coordination, requiring a lot of trust, and communication. - **Other:** Real-time monitoring, Trial and error, Graceful degradation.	(Zwieback, 2014)
SELFMAN A R	**Purpose:** Project aimed at building self-managing applications for large-scale distributed systems on structured overlay networks. **How:** SELFMAN has combined two technologies, namely structured overlay networks (SONs) and advanced component models (ACM), to make the system self-managing in the face of disruptions and complexity. SON developed out of peer-to-peer systems and provided robustness, scalability, communication guarantees, and efficiency. This topology, with atomic ring maintenance (handling network partitioning, handling failure suspicions, and handling range queries with load balancing), exhibits self-organizing properties, i.e., surviving node failures, node leaves, node crashes, and node joins while maintaining its specification. The integrated features as described below do help to achieve application resiliency and even blend into antifragility. **Covered strategies/capabilities:** - **Self-management:** Including (1) self-configuration / self-organizing, (2) self-healing, (3) self-tuning, and (4) self-protection. - **Feedback mechanisms:** Service architecture containing many interacting feedback loops that continuously monitor parameters, calculate a response and update the system. - **Phase transition:** Covering properties of phase transitions by identifying the behavior of each phase on node failure rates. - **Other:** Fragmentation, Auto-scaling.	(Chikumbo and Norris, 2015)
Scalaris A	-**Purpose:** Scalable transactional data store for global online services based on the peer-to-peer principle (online shopping, internet banking, data sharing, online gaming, or social networks). **How:** Without system interruption, it scales from a few PCs to thousands of servers. Scalarix requires "little or no human intervention in management tasks such as adding or removing nodes" (services) for large-scale distributed networks without any service downtime, protecting system components, responding to component breakdowns, and even deliberate attacks. Scalaris due to the following features can be considered an example of antifragility: **Covered strategies/capabilities:** **Self-healing:** To recover when it detects a computing node crash or problem. **Self-tuning:** To distribute the load evenly over the system automatically to improve response times. **Auto scaling:** By replicating services among peers.	(Chikumbo and Norris, 2015)

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Table 7 (*continued*)

Example	Description	References
Health 3.0 A	**Purpose:** New healthcare framework (open healthcare information architecture) which uses social media and reasoning tools to enhance interactions between health care providers and patients. **How:** Involving both the patient and the healthcare provider in the decision-making model. While in older healthcare frameworks the focus was on hospital and curative treatment (health 1.0), or on doctors and preventive medicine (health 2.0), in 3.0 the focus moves to patient-doctor relationship and preventive/alternative therapy. Health 3.0 promotes an antifragility approach through the following ways: **Covered strategies/capabilities:** - **Collaboration:** Increasing patient self-management by (1) improving access to health-related information, and (2) creating supportive virtual communities. - **Via Negativa:** By eliminating things to have a much more rational and inexpensive health care system. - **Optionality:** Medical decision-making should be filled with rational options to reward the things that work and limit and learn from the things that don't. - **Other:** Decentralization, Skin in the Game, Tinkering and heuristics, Trial and Error.	(Julapalli, 2015)
Kubernetes R A	**Purpose:** Open-sourced platform by Google to automate, deploy, scale, and manage the health of containerized applications and services over time. **How:** A flexible container orchestration technology that can spread the service instances on multiple nodes using an anti-affinity feature to reduce correlated failures. The integrated toolset in Kubernetes (featuring decentralization, container resource isolation, health checks, observability, optionality, auto-scaling, configuration management, etc.) do help achieve application resiliency, self-healing and even blend into antifragility. **Covered strategies/capabilities:** - **Real-time monitoring:** Regular health checks of the running containers. - Fallback and graceful degradation: Restarting the container and bringing the application back to a healthy state when an anomaly is detected. - **Other:** Auto-scaling, Auto deployment, Self-awareness.	(Ibryam, 2016)
BitTorrent A	**Purpose:** Peer-to-peer file sharing protocol, allowing fast downloading of large files using minimum Internet bandwidth. **How:** BitTorrent can be considered as an example of antifragility because the more a file is popular for downloads, then its parts are available from more peers and become traffic hotspot. Therefore, the more a file is requested (stressor), the faster it gets to download it from many peers available. The best-case scenario for data stored on BitTorrent is the rare, entirely unpredictable event (the rapid increase of demand) in which every person on earth wants to download it and then share it. **Covered strategies/capabilities:** - **Fragmentation:** Idea of democratizing the Web by enabling decentralized, resilient access to information. - **Auto scaling:** Streams gain from hotspots and allow users to download and upload from each other simultaneously and exploiting the network effect to provide auto-scaling. - **Redundancy:** The more a copy of a file is requested, the more robust to failure and available it gets, and practically becomes impossible to delete it because parts of it are stored on a progressively more significant number of computers.	(Zwieback, 2014; Chikumbo and Norris, 2015)
Reactive jammer piggybacking A	**Purpose:** A PhD thesis introducing a case of application "of antifragility to wireless communications where the system stressor is a jammer that intends to disrupt the underlying communications" for the domain of electronic warfare. **How:** Gain is achieved by harnessing the presence of a stressor (jammer). The idea is using a jammer exploitation strategy (instead of avoiding or mitigating jamming) in which the communications system causes an enemy reactive jammer to distract or transmit desired information or perform any other action that could lead to communication gain. **Covered strategies/capabilities:** - **Fault injection**: Exploiting reactive communications jammer through antifragile waveforms and jammer piggyback waveforms. - **Achieving Coarse Time Synchronization:** Allowing a wireless network to increase synchronization capability as a result of an attack. - **Hedging:** By hiding the desired signal within an enemy jammer's signal while maintaining communications. - **Other:** Modularity, Reinforcement learning.	(Lichtman et al., 2016)

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Table 7 (*continued*)

Example	Description	References
Bitcoin A	**Purpose:** A decentralized digital cryptocurrency that can be sent from user to user on a peer-to-peer network. **How:** Each time Bitcoin is exposed to disruptions, it may be failed, but it is reinvented. Either the core developers upgrade its code or develop other solutions to ensure stronger defense against the next stress. **Covered strategies/capabilities:** - **Fragmentation:** Large-scale decentralized and distributed network. - **Building trust:** Owned by its users (the crowd), and no authority can decide on its fate. Bitcoin evolves through the necessary actions of its members/miners. - **Optionality by "via negativa":** To experiment and eliminate what does not work; everyone can innovate on the protocol and benefit from positive events without the negative impact of the failed experiment. Bitcoin is concerning maximizing investment in convexity and thus positive outcomes from optionality. - **Lindy Effect:** Survived a meaningful amount of time in a volatile and competitive environment. - **Skin in the Game:** "Miners" have the most skin in the game and hence, they get to decide what to do with their capital. - **Adaptability:** E.g., there are rules set in the protocol that can be changed if most actors of the network accept the new set of rules. - **Redundancy:** Redundancy layers which are critical to the resiliency of the system.	(González et al., 2017)
An Antifragile Cloud Computing Infrastructure A	**Purpose:** a solution to design an antifragile cloud infrastructure that learns from failures deals with randomness and becomes stronger. **How:** Randomly killing off virtual machine instances in a cloud when a virtual machine gets disrupted, a new and healthy virtual machine is generated to take its place. This ensures building an antifragile cloud infrastructure that learns from failures to create a new and more robust virtual machine. **Covered strategies/capabilities:** **- Fault injection:** Randomized virtual machine killing improves the resilience and availability of the system. **- Real-time monitoring:** Providing information gathering from the virtual machine to respond failures adequately. **- Learning:** Unsupervised learning approach to identify known and unknown anomalies.	(Abid et al., 2014)

this shift to healthcare products it could survive in contrast to many other textile companies (Edstr, 2017).

- JC Jeans Company; the fourth largest clothing retailer in Sweden (mid-1990s), declined after some changes and the loss of key managers and employees who had created an environment for innovation and success in the company. Nevertheless, the JC's entrepreneurial spirit and position in the clothing business ecosystem was like a progress ladder for a future generation of entrepreneurs as some of former employees founded new companies which are very successful now, thus a case of transformative resilience (Edstr, 2017).
- Osteria Francescana; a three Michelin stars restaurant in Italy, is a good example of transformative resilience. The owners decided to modernize traditional Italian cuisine, by combining the essence and tradition of the countryside with the principles of modern cuisine and art: Innovation, competition, globalization, liberation, and learning from mistakes. They went through a tough period of failures and rejection by local community, which they took to nurture a culture of persistence and innovation, through developing a failure positive atmosphere, until they became a top restaurant in the world. A good illustration of this attitude is the most famous dish of this restaurant - "Oops! - a broken lemon tart served in a broken plate. It was inspired on an accident when a chef prepared two lemon tarts but at the time of serving them, he broke one of them on the counter. While the chef was very upset, the restaurant owner could realize that the broken tart looked beautiful and decided to create the same situation in another plate with the same elements. This iconic dish illustrates a thrive in life and the aim of learning from mistakes (Marston and Marston, 2018).

***Industry*.** Airline industries get stronger after a plane crash because a failure in a single airplane is isolated from others and by learning from failures, they adapt the other planes to prevent the same type of failure and another disaster. As such, a short-term increase in aviation accidents can lead to higher overall safety in the industry (Taleb, 2012; Verhulst, 2014). Restaurant industry could also be considered as an antifragile system composed of fragile components which are independent of each other; the failure of individual components strengthens the industry as a whole, through learning from mistakes (trial and error) (Devendorf et al., 2017). In business ecosystems, there are several positive stressors such as competition, constraints (censorship, redlines, "necessity is the mother of invention"), challenges to find a better solution to solve a problem (tinkerers), and constructive criticism, that force business to overcompensate and grow in the long run. As an illustration, "Silicon Valley" based companies such as Facebook, with stochastic tinkering at all levels, are antifragile when they innovate a lot and admit failure (Taleb, 2012; Monperrus, 2017; Mougayar, 2013). To achieve this, they rely on continuous delivery, coupled with massive automation (Pink, 2011).

***Technology*.** Materials such as carbon nanotubes and fluids that get stronger when facing a stressor are examples of antifragility (Chikumbo and Norris, 2015). Internet with its robust flow control, alternative routing, and error control, that survived about three decades while facing different disruptions, can be considered as an engineered example of antifragility. As the Internet matured, it gets stronger through exposure to attacks (Lucky, 2013). An illustrative story relates to the attempts of the Iraqi Ministry of Communications (MOC) to shut down the internet in Iraq and force service providers to accept new cost regulations. But, MOC succeeded in only causing a minor disruption before full service was resumed because of the inherent resilience of Internet (Devendorf et al., 2017). Multiple-input-multiple-output (MIMO) techniques, which deliberately send multiple copies of a signal from different antennas, hoping there will be multipath phenomena to "enhance system performance, can be considered as an example of antifragile communications" (Lichtman et al., 2016).

4.3.2. Real-world engineered examples

Table 7 includes several real-world examples of resilient / antifragile systems. Although not a comprehensive list, these examples demonstrate that these concepts are more than a mythical idea. The classification of examples as R (resilience case) or A (antifragility case) comes from the literature analysis. Often the indicated references explicitly classify the example, or it can be derived from the exposed properties.

5. Conclusions and discussion

Understanding and designing approaches for increasing the level of resilience and even reaching antifragility are crucial for the success of business ecosystems in times of growing uncertainty and disruptive events. Furthermore, considering the role played by business ecosystems in society and how societal entities are more and more hyper-connected, their success is complementarily relevant to the whole socio-economic system.

As this literature survey shows, there is already a large amount of strategies and mechanisms to promote resilience and antifragility, but they appear rather dispersed, often reflecting partial views, and using inconsistent terminology. In a clarification attempt, this work includes a collection of related definitions, identification of disruption sources and classification disruption drivers. Furthermore, an extensive effort was put on organizing and classifying collected strategies and underlying capabilities, providing a basis for further analysis. In terms of identified strategies, an indication is given on which property – resilience and/or antifragility – they mainly relate to. Furthermore, considering the main typical phases of disaster (disruption) management – readiness, response, and recovery – an indication of which phase is mainly covered by each strategy is also provided. A similar effort was made to provide a classified portfolio of capabilities that can be developed inside organizations and activated by strategies to cope with disruptions, indicating in which area – resilience and / or antifragility – each capability is more applicable. These classifications are intended to give researchers and practitioners an integrated and organized overview of the area and available / emerging approaches and mechanisms.

On the other hand, it was observed that several knowledge areas address these issues and part of this work focused on identifying relevant contributions from various areas, providing a reference mapping. Finally, a set of illustrative examples of engineered systems were collected and analyzed, which help getting insight on current practices and promising approaches.

As such, the significance of the results of this work is reflected in:

- Contributions to a theoretical framework on resilience and antifragility. The effort to collect, integrate, and classify a vast array of fragmented contributions from a large number of research works originated in different disciplines, provides a new starting base for researchers in this area. In addition to an effort to clarify concepts, three main results are of relevance here: (1) The identification and categorization of disruption sources and drivers, (2) The collection of disruption handling strategies and their categorization in terms of phase of applicability and scope, and (3) The identification and categorization of relevant capabilities that can be activate in response to disruptions. The relationship between strategies and capabilities is also clarified. Nevertheless, it is important to notice that this work is focused on business ecosystems and which strategies and capabilities are relevant for such organizational structures.
- Contributions to practice. Although the focus of this work was not on the development of specific tools, the results have also some relevance to both ecosystem managers and entrepreneurs, namely by offering them a comprehensive overview of the strategies they can adopt, their potential and limits, as well as the portfolio of capabilities they may develop in their organizations to be prepared to better deal with disruptions. Of special relevance here is the collection of relevant examples, which illustrate how these elements can be used in practice.

Further work is needed in order to assess the conditions of applicability of these strategies to each type of business ecosystems. This will provide important elements on how to organize and govern such systems and will likely inspire the development of new support tools. Other directions can as well be explored, as for instance, the potential that these strategies and capabilities can have in supporting disruptive innovators. Some hints on how disruptions can be used to motivate innovation can be derived from the antifragility support strategies, but this aspect requires further work.

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