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Supply chain resilience: a dynamic and multidimensional approach

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Abstract

Purpose – The purpose of this paper is to present a conceptual framework on resilience types in supply chain networks.
Design/methodology/approach – Using a complex adaptive systems perspective as an organizing framework, the paper explores three forms of resilience: engineering, ecological and evolutionary and their antecedents and links these to four phases of supply chain resilience (SCRES): readiness, response, recovery, growth and renewal.
Findings – Resilient supply chains need all three forms of resilience. Efficiency and system optimization approaches may promote quick recovery after a disruption. However, system-level response requires adaptive capabilities and transformational behaviors may be needed to move supply chains to new fitness levels after a disruption. The three resilience types discussed are not mutually exclusive, but rather complement each other and there are synergies and tradeoffs among these resilience types.
Research limitations/implications – The empirical validation of the theoretical propositions will open up new vistas for supply chain research. Possibilities exist for analyzing and assessing SCRES in multiple and more comprehensive ways.
Practical implications – The findings of the research can help managers refine their approaches to managing supply chain networks. A more balanced approach to supply chain management can reduce the risks and vulnerabilities associated with supply chain disruptions.
Originality/value – This study is unique as it conceptualizes SCRES in multiple ways, thereby extending our understanding of supply chain stability.

Keywords North America, Supplier relations, complex adaptive systems, Supply chain management, Engineering, Conceptual research, Response flexibility, Ecological and evolutionary resilience, Supply chain networks

Paper type Conceptual paper

Introduction

Disruptions to commercial supply chains can have significant economic impacts. Managing risk and vulnerability associated with supply chains have therefore assumed some urgency. Resilience, the capacity of a system to adapt to change and deal with surprise while retaining the system's basic function and structure (Holling, 1973), has emerged as an important tool for managing supply chain risk and vulnerability (Ponomarov and Holcomb, 2009; Pettit *et al.*, 2010).

Early research on supply chain resilience (SCRES) focused on resilience as a means for reducing risk and vulnerability in supply chains (Martin and Peck, 2004) and as an organizational capability that confers competitive advantage (Sheffi, 2005). That stream of research discusses resilient supply chains as capable of absorbing or avoiding disruptions entirely (Sheffi and Rice, 2005), or recovering much faster after a disruption (Zsidisin and Smith, 2005). Researchers have also focused on strategies that firms can use to build resilient supply chains (Wieland and Wallenburg, 2013), as well as factors that both reduce

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and enhance resilience in supply chains (Blackhurst *et al.*, 2011). New efforts to assess SCRES are emerging. For example, Barroso *et al.* (2015) calculated what they call the resiliency index of a supply chain by measuring the disruptive capacity as the recovery time of a supply chain following a disruption and recent reviews have begun to categorize studies into typologies. For example, Tukamuhabwa *et al.* (2015) categorized resilience strategies into proactive and reactive strategies. Our understanding of supply chain dynamics has been enhanced by the ongoing focus on resilience. Despite this progress, some gaps remain in our understanding of both the concept and its usefulness in explaining supply chain dynamics.

First, resilience by definition is a dynamic concept. Specifically, because resilience is a property of dynamic systems, it is important to focus on system attributes and the dynamic structure of supply chain networks. As Walker *et al.* (2004, p. 1) noted, "resilience of a system needs to be considered in terms of the attributes that govern the system's dynamics." Second, while resilience is clearly a multidimensional construct, few studies in the supply chain literature have explicitly addressed this (see Eltantawy, 2016 for an exception). Third, although resilience has been conceptualized in terms of a supply chain's ability to be ready, respond, recover and transform (Tukamuhabwa *et al.*, 2015), not much is known about the capabilities for managing the growth and transformation phases. Finally, the emerging SCRES literature has been largely atheoretical and other researchers (e.g. Tukamuhabwa *et al.*, 2015; Ali *et al.*, 2017) have noted this. Researchers have used the resource-based view (Blackhurst *et al.*, 2011), social capital (Johnson *et al.*, 2013) and complex adaptive systems (CAS) theory (Day, 2014; Tukamuhabwa *et al.*, 2015) to explain resilience. There is a need to adopt theoretical lenses more in tune with the dynamic nature of supply chains.

This research extends existing research by developing a multidimensional framework of SCRES and in so doing bridges some of the existing gaps. We adopt a CAS perspective as an organizing framework to emphasize the dynamic and nonlinear nature of supply chain networks (Pathak *et al.*, 2007; Tukamuhabwa *et al.*, 2015). We explore three forms of resilience: engineering, ecological and evolutionary resilience and their antecedents and link these to the overall system resilience, defined as the ability of a supply chain to be ready, respond, recover and have the capacity for renewal following a disruption. The rest of the paper is organized as follows to explore the issues. The first section identifies and discusses the three forms of resilience. This section explores the key antecedents (SCRES elements) of each resilience type as well as the strategies and capabilities required for each resilience type. The section after that discusses the synergies and tradeoffs inherent in the multidimensional concept of resilience. The next and concluding section presents a discussion of both the practice and research implications of the paper.

Figure 1 presents a summary of the conceptual framework of the paper. It relates SCRES capabilities to different resilience types and to the four phases of SCRES. The resilience types do not just have direct effects on the phases of SCRES, they may interact with each other and there are inherent tradeoffs between them. The key presumption is that a resilient supply chain must be able to navigate all the stages of disruption. This means that resilient supply chains have the capabilities to respond, recover and transform after a disruption. Pettit *et al.* (2010) in fact suggested that the desired level of resilience is achieved when there is a match between vulnerabilities and corresponding capabilities. We suggest that although there are different types of resilience, ideally resilient supply chains need to have not just some, but all the three types of resilience. More important, there may be synergies as well as tradeoffs among the resilience types.

This paper makes a number of significant contributions to research on resilience in supply chain networks. First, we explore the multidimensional nature of resilience in supply chain networks. As Pettit *et al.* (2010) noted, we need a broader view of resilience than

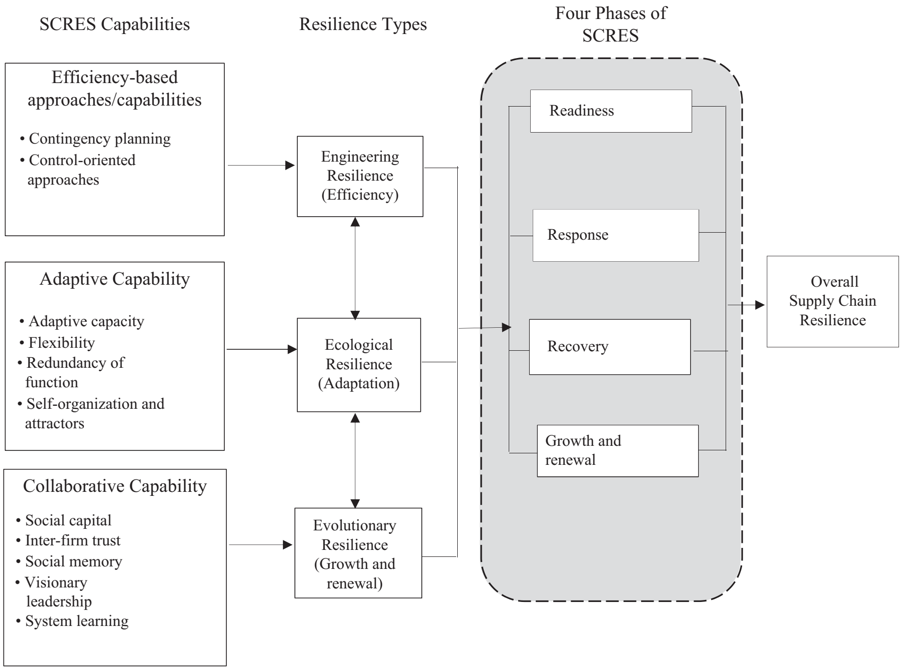

Figure 1. Proposed framework of supply chain resilience

existing research suggests. Eltantawy (2016) made an important conceptual advance by identifying two types of resilience: engineering and ecological resilience in supply chains. We extend this line of research by adding a third form of resilience, evolutionary or socio-ecological resilience. As Eltantawy (2016, p. 126) noted, "Construct specification is crucial at this early stage of delineating the resilience construct." While this study builds on Eltantawy (2016), it goes beyond that to avoid missing important elements of resiliency that have yet to be applied in the supply chain literature. Second, our use of the CAS framework allows us to link resilience to supply chain structure, thereby allowing us to show the capacity of resilience to vary across phases of supply chain evolution. This is important given that there are different forms of resilience, and that resilience may vary across different phases and multiple periods of a supply chain since, by nature, supply chains exhibit nonlinear dynamics (Blackhurst *et al.*, 2011). Third, this research extends existing research by building on Maruf *et al.* (2016), who developed a model of supply chain readiness and response–recovery capability. Our model goes beyond that and discusses renewal and growth or transformation capability. As Bristow and Healey (2014) observed, the essence of resilience is to change as circumstances change, to adapt, and when necessary, transform rather than continuing to do the same thing better. Fourth, we explore the interplay between the various resilience types to offer a more holistic explanation of SCRES. Finally, the framework provided in this research may allow us to derive a set of practical guidelines for building resilience in supply chain networks.

There is emerging agreement that SCRES requires a set of distinct characteristics. In their systematic review of the SCRES literature, Hohenstein *et al.* (2015) identified four distinct phases of SCRES: readiness, response, recovery and growth or movement to a new and more desirable state after a disruption. These four phases cover the pre- and post-disruption phases of supply chain risk management (Barroso *et al.*, 2015). Building on earlier research, Hohenstein *et al.* (2015) identified four distinct phases of

SCRES: supply chain readiness, response, recovery and growth. A brief annotation of these four phases may be helpful to our understanding of how to manage resilience over time. Growth goes beyond recovery; it not only returns a system to its pre-disruption state, but more important, goes beyond that to achieve a new and improved position (Hohenstein *et al.*, 2015). Carvalho *et al.* (2012, p. 331) in fact defined SCRES in terms of this capacity for growth by noting, "Supply chain resilience is concerned with the system ability to return to its original state or to a new, more desirable state."

Supply chains as complex adaptive systems

Supply chains have been conceptualized as CAS (Pathak *et al.*, 2007; Wycisk *et al.*, 2008; Choi *et al.*, 2001). With roots in systems, complexity and chaos theory, CAS are systems that emerge into a coherent form through adaptation and self-organization (Holland, 1995). CAS consist of a number of active agents, who interact with each other according to sets of rules that require them to examine and respond to each other's behavior in order to improve their behavior and the behavior of the system they comprise (Stacey, 1996, p. 10). In the case of supply chains, the agents (firms) interact by exchanging information and physical goods (Pathak *et al.*, 2007). Agents in a CAS are heterogeneous with degrees of freedom to act independently when necessary even as they share connectivity with other members (Choi *et al.*, 2001). Although operating at different levels (Surana *et al.*, 2005), their collective goal is to enhance the fitness of the system. By its agents trying to achieve individual goals, the supply chain benefits from a collective outcome. Similarly, a negative event in one firm in the supply chain may have system-wide repercussions (Barroso *et al.*, 2015).

CAS have some other common characteristics. CAS interact with their environment, adapt and co-evolve to create dynamic, emergent realities (Wycisk *et al.*, 2008) and SCRES has been described as an adaptive phenomenon (Aditya *et al.*, 2014). Supply chains face a dynamic environment and need to adapt as changes occur in the environment if they are to survive (Choi *et al.*, 2001). At the same time, the activities of individual agents also influence the supply chain environment. CAS exhibit nonlinearity, which makes determining cause and effect or making predictions about nonlinear phenomena difficult, if not impossible. This may be so because large changes in input in such systems may lead to small changes in outcome, and small changes in input may lead to large changes in outcome, the so-called "butterfly effect" (Choi *et al.*, 2001, p. 356), a phenomenon much akin to the "bullwhip" effect in supply chains. Small events then are perfectly capable of causing severe disruptions or having massive effects on supply chain networks, as there is no direct correlation between cause and effect. In addition, agents in a CAS share common schema or norms of behavior (Choi *et al.*, 2001) and firms in supply chains similarly have rules and policies that govern their relationships. Next, CAS exhibit self-organization and emergent behavior, a process by which order emerges without any external control (Nicolis and Prigogine, 1989) and supply chains have been described as self-organizing systems (Choi *et al.*, 2001; Nilsson and Gammelgaard, 2012). SCRES itself has been conceptualized as an emergent phenomenon (Day, 2014). Related to supply chains, this quality of CAS means that individual actor decisions can cause new structures to emerge in the supply chain although no single firm can determine the resilience of the entire supply chain (Geng *et al.*, 2014). CAS have the ability to engage in dynamic learning as a strategy to attain fit with their environment because learning helps adaptation (Wycisk *et al.*, 2008). Finally, CAS undergo transformation. Transformation involves radical change that results in a fundamentally different system. Walker and Salt (2006) defined transformation as changing the "state of the system," reflected in changes to such system characteristics as goals, scale and cross-system connections in space and time. The qualities of a CAS and the description of a supply chain as a CAS implies that resilience itself may best be understood as a dynamic and nonlinear concept since resilience is a feature of such dynamic systems (Nilsson and Gammelgaard, 2012).

SCRES: a multidimensional construct

One of the more frequently cited definitions of SCRES is based on Christopher and Peck (2004, p. 2) who define resilience as "the ability of a system to return to its original state or move to a new, more desirable state after being disturbed." We suggest that at least three forms of resilience are necessary if supply chains are to accomplish those goals. Borrowing from Holling's (1973) seminal work on resilience, we can identify two forms of resilience: ecological and engineering, each with very distinct design and management goals. Both concepts of resilience are alike in one respect: both envision a system that has been pushed off its equilibrium state by a disturbance but they differ in terms of the mechanisms and strategies the systems use to avoid being pushed so far as to be functionally restructured (Ruhl, 2011). Related to supply chains, any disruption to the supply chain stability can be equated with a system being pushed off its equilibrium.

Engineering resilience

Holling (1973) defined engineering resilience as the ability of a system to return to an equilibrium or steady state after a disturbance. Resistance to disturbance and the speed at which the system returns to equilibrium is the measure of engineering resilience. According to this form of resilience, the faster a system bounces back, the more resilient it is. The emphasis here, as Holling (1996) puts it, is on return time. "Efficiency, constancy and predictability-all attributes at the core of the engineer's sought-after qualities for a fail-safe engineering design" (p. 63). According to Ruhl (2011, p. 4), "engineering resilience draws on reliability, efficiency, and quality control and similar strategies to pursue a single objective- return the system to equilibrium state" after a disturbance making recovery a design goal. Accomplishing the goals of efficiency and reliability requires supply chain members to develop some key capabilities.

First, contingency planning (CP) is an effective tool for engineering resilience. CP involves developing responses in advance for managing disruptions that may impact the supply chain. CP requires risk analysis and determination of the likelihood of impact of disruption and the development of response alternatives. A key aspect of CP is the development of the capacity to develop an early warning system with which to forecast and monitor possible disruptions to the supply chain before they occur (Sheffi, 2005; Tang, 2006; Pettit, 2008). Contingency plans can be developed around how to reconfigure the supply chain in the event of a disruption, recovery and restoration plans in the event of a disruption, as well as resource and supply chain reconfigurations (Ambulkar *et al.*, 2015; Sheffi, 2005; Pettit *et al.*, 2010).

Second, firms can use both supply and demand management capability as a strategy for managing disruptions (Tang, 2006). Strategies such as the use of postponement, using delayed product differentiation (DPD) strategy to minimize costs by delaying additional investment into a product until the last possible moment is a way to reduce risk (AlGeddawy and ElMaraghy, 2012). DPD is a prerequisite for applying postponement strategies. Postponement strategy involves designing generic products based on total aggregate demand of all products and delaying customizing the generic product later on using process design concepts such as standardization, commonality and modular design to delay the point of differentiation (Tang, 2006; Sheffi, 2005). Postponement can come in different forms: place, form, time, labeling, packaging, assembly and manufacturing (Swaminathan and Tayur, 1998). Agents can also use flexible supply bases so that production can be quickly shifted among suppliers as a robust strategy for minimizing the impact of disruptions. Benetton, UPS, HP and Nokia have been mentioned as examples of firms that use these and related approaches to manage resilience in supply chains (Sheffi, 2005; Tang, 2006).

Third, firms can use Business Continuity Planning (BCP), as a strategy for managing supply chain risk and disruptions. BCP is a tool for managing supply risks that are typically difficult to predict, have a very low probability of occurrence, but nonetheless have a potentially catastrophic impact on the organization if they happen (Zsidisin and Smith, 2005). BCP involves identifying the critical suppliers in the chain, ascertaining the potential impact of the loss of such a supplier by conducting a business impact assessment as well as a risk assessment to understand the potential risk that would affect the supplier. To deal with risk, a BCP program requires firms to know who the critical suppliers are so that they can draw up detailed strategies to deal with any disruption affecting them. BCP involves a continuous process of risk awareness and monitoring of the supplier chain with near misses and drops in quality promptly investigated. Recognizing early warning signs is a key part of this approach (www.thebci.org/).

Fourth, building an agile supply chain can increase engineering resilience. Supply chain agility is the ability of a supply chain to respond quickly to changes in supply and demand (Christopher and Peck, 2004). An agile supply chain has two characteristics: visibility and velocity. Visibility enables supply chain actors to be able to see through the entire supply chain as well as know the system's environment and its key assets. Visibility also allows the firms to identify vulnerable suppliers so that they can prepare contingency plans for reaction in the event of a disruption (Ying *et al.*, 2013). Visibility can be enhanced through the development of monitoring programs like BCP, information sharing and transparency. The use of these and similar integrated systems may be an important means for mitigating the impact of large-scale disruptions (Ponomarov and Holcomb, 2009; Ambulkar *et al.*, 2015). Sáenz and Revilla (2014) cited the example of Cisco using this capability to improve its agility and response to the 2011 Japanese tsunami. Supply chain velocity is another determinant of agility and engineering resilience. Carvalho *et al.* (2012) defined velocity as the ability to complete an activity as quickly as possible. For example, the total time it takes to move products and materials from one end of the supply chain to the other expresses velocity (Christopher and Lee, 2004). Supply chain velocity itself may determine the recovery speed of the supply chain from a risk event (Tukamuhabwa *et al.*, 2015).

Finally, other engineering resilience strategies such as lean manufacturing, just-in-time (JIT) delivery may help short-term response. Indeed, Marchese *et al.* (2012) noted that supply chain strategies focused on reducing operational risk depend on lean manufacturing, JIT inventory and capacity rationalization to boost supply chain efficiency. Qrunflesh and Tarafdar (2013) suggested that lean supply chain management actually helps supply chain performance. To the extent that these approaches rely on the notion of planning for risk and designing a fail-safe system, they are reflective of engineering resilience. Engineering resilience and the associated capabilities discussed here are clearly assets that would allow supplier chain actors to react promptly and recover from disruptions. By definition, recovery is the criterion variable in engineering resilience.

At some level, engineering resilience rests on a traditional Cartesian-Newtonian worldview of control, efficiency and system optimization. That approach views supply chains as static systems in which the goal is system optimization (see e.g. Gunasekaran and Ngai, 2004; Pathak *et al.*, 2007). As Holling and Gunderson (2002) observed, engineering resilience devotes all its resources to staying near the equilibrium, so that the system can snap back after a shock. The authors warn, however, that focusing on engineering resilience exclusively "reinforces the dangerous myth that the variability of systems can be effectively controlled, that the consequences are predictable." As Holling (1996, p. 34) observed, the search for optimal systems implies that systems have global stability and that only one equilibrium steady state exists, and if others exist, "they need to be avoided." Accordingly, engineering resilience strategies such as efficiency would remove, at the design stage, anything perceived as wasteful redundancy. However, engineering resilience is only useful in the end if possible, or most inefficiencies are known and removed at the design stage, a situation that is not always possible. Indeed, engineering resilience strategies can only be useful when variability is low and future conditions can be predicted over a reasonable period (Ruhl, 2011).

A system that favors engineering resilience will tend to be highly resistant to change because of this inherent rigidity. Such a system, however, would be vulnerable to large-scale disruptions if internal and external shocks break its resistance. Indeed, as Choi and Hong (2002) observed, firms using universal quality standards such as ISO 9000 and "Six Sigma" may be trying to impose too rigid control on complex systems. The authors cited the examples of such notable firms as Motorola, IBM and Daimler Chrysler as examples of firms who tried, unsuccessfully, to use institutional strategies to achieve efficiency in their supply chains. The authors noted that popular control-oriented schemes such as JIT may be substituting short-term efficiency for long-term performance in supply chain networks. Fisher (2011) similarly reported on one downside of this engineering resilience approach by some Japanese supply networks. The author noted that some supply networks had a hard time recovering after the 2011 tsunami disaster because in trying to provide better quality at lower prices, manufacturers picked very narrow, optimized supply chains, thereby "risking everything on one endeavor" so to say. Fisher (2011) suggested that a number of Japanese companies have learned the lessons of focusing on too much efficiency (engineering resilience) and have already started investing in redundancy with Canon, for example, reported to be considering a move to diversify its production base by expanding from its southern Japan sources and increasing production lines at its two factories in China.

The effectiveness of most of the engineering resilience strategies discussed here are predicated on one key condition: our ability to predict the future, or at least be able to isolate all the possible risk parameters and then either plan for them or eliminate them at the planning or design stage. BCM, agility with its visibility dimension, demand and supply management as part of CP all presuppose that we can somehow be able to envisage an uncertain future. Yet, we have shown that supply chains as CAS demonstrate nonlinear behavior, and predictability is limited (Choi *et al.*, 2001, Wycisk *et al.*, 2008). If one can predict system evolution and future problems of the system with some certainty at the design stage, then efficiency and engineering resilience strategies would seem appropriate. If the reverse is true, the long-term stability of a system with high engineering resilience may be in doubt because such systems tend to be rigid and unable to adapt making them vulnerable to both internal and external shocks. There are other reasons to suggest that engineering resilience alone would be insufficient. First, managing for efficiency may actually breed a culture of short-term thinking. Second and related, there may be a loss of resiliency because the functional diversity of a system diminishes as engineering resilience increases.

In the end, engineering resilience can allow agents to recover quickly from a disruption. This, however, may be at the expense of long-term stability and performance of the supply chain. Agility promotes quicker response, but reductions of slack in the supply network also reduces the margin for error, thereby amplifying disruptions, making firms more susceptible to vulnerability in the long term because the approach substitutes efficiency for wider recovery options in the event of a shock to the system (Zsidisin and Smith, 2005). Other resilience forms may therefore be needed to supplement engineering resilience to cushion some of the limitations of engineering resilience discussed here. Therefore, the following is proposed:

P1a. Efficiency-based SCRES elements are positively associated with engineering resilience.

P1b. Engineering resilience is positively associated with recovery after a disruption.

P1c. Engineering resilience is a necessary, but not sufficient, condition for SCRES.

Ecological resilience

Managing system-wide response requires adaptive behaviors and coordination between members of the network. Behaviors and capabilities relating to adaptive capability are more consistent with ecological resilience. Ecological resilience is measured by the "magnitude of disturbance a system can sustain before a change in system control and structure occurs" (Holling, 1996, p. 33). This form of resilience relies on adjustments to system processes as a means of managing overall system integrity and favors resistance, and the engineer's search for "fail-safe" as the design goal. Unlike engineering resilience, ecological resilience is defined not by how long it takes a system to bounce back after a shock, but by how much disturbance the system can take while remaining within some critical threshold. Ecological resilience is about adaptation. As Davoudi (2012) noted, a critical difference between ecological and engineering resilience is that while the latter accepts the existence of a single, stable equilibrium state, the former acknowledges the existence of multiple equilibria and the possibility of systems to flip into alternate stability domains. Supply chain actors can use a number of strategies and capabilities to manage adaptation to promote system-wide recovery.

Ecological resilience can be maintained using functional redundancy and a diversity of system components. Gunderson and Holling (2002) defined functional redundancy as the "diversity of the responses to disturbance among the species or actors contributing to the same function in social-ecological systems." Functional redundancy implies the presence of multiple components that can perform the same function so that a failure of one component is not fatal to the system as other components in the system can compensate for the loss in the system. Redundancy opens up the response diversity of a system. Response diversity enhances resilience because it opens up options.

Related to supply chains, redundancy involves the strategic use of spare capacity and inventory to manage disruptions (Christopher and Peck, 2004). Redundancy duplicates capacity, which can be used during a disruption, thereby increasing flexibility and facilitating response during disruptions. Operational slack, a form of excess capacity, has been found to lower the likelihood that negative stock market reaction will occur during a disruption (Hendricks *et al.*, 2009). Other researchers have also emphasized flexibility in the form of safety stock and excess capacity as a strategy for mitigating the negative impact of supply chain disruptions (Tang, 2006; Azadegan *et al.*, 2013). Sheffi's (2005) account of the impact of Hurricane Mitch in 1998 on Chiquita and Dole, two competing firms, is revealing. His account shows that the impact of Hurricane Mitch on banana supplies for Chiquita and Dole was different. Dole lost 25 of its global banana suppliers because of the hurricane, but because Chiquita had more varied suppliers from such far-flung places as Ivory Coast and Australia, it moved quickly to leverage these other suppliers. Biggs *et al.* (2015) argued that redundancy is more valuable when response diversity of a system is higher, especially where the components providing the redundancy function also react differently to change and disturbance. As the Chiquita example demonstrated, the hurricane in South America did not affect banana producers in West Africa and Australia. The lesson here is that firms can build redundancy into their supply chains to enhance their ecological resilience (Fiksel, 2003; Pettit *et al.*, 2010). Of course, redundancy as a strategic option for increasing resilience comes at a cost: it may promote some inefficiency and higher transaction costs because of capacity duplication (Rice and Caniato, 2003) and, unless there are disruptions, there is underutilization of resources. Sheffi (2005) suggested ways that supply chain members can build redundancy into supply chains without increasing costs by using flexible contracts and by using standard, rather than special parts, amongst others. Despite the inherent costs of using diverse response options, the nature of the dynamic environment in which supply chain networks as CAS operate makes having these additional options a good strategic option.

Second, supply chain actors can create the conditions for self-organization in the supply chain as a means for enhancing ecological resilience. As CAS, supply chains exhibit self-organization and emergence (Choi *et al.*, 2001; Nilsson and Gammelgaard, 2012). Self-organization involves the rise of emergent phenomenon. Related to supply chain networks, ecological resilience emerges when individual decisions made at the firm level by agents (firms) generate new structures at the system or supply chain level. Clearly, some agents may have more advantage or power than others may, but the key here is they still cannot control the supply chain in its entirety. As Geng *et al.* (2014) noted, no single firm controls the resilience of the entire supply chain. All firms in the supply chain have the same goals: produce quality, satisfy demand and make profits. Each tries to achieve these goals individually and that process produces a collective outcome for the system as a whole. In complexity theory terms, the common desires may be similar to the concept of "attractors." According to Coleman *et al.* (2007), attractors represent the long-term dynamics of a system so that whatever the initial conditions, systems over time get "attracted" to the attractor in their basin.

Although no individual firm can control what happens to resilience as an emergent aspect of supply chains, emerging research in dynamical systems theory (Coleman *et al.*, 2007) may offer some guidelines to how the actors can at least facilitate individual actor behaviors that lead to the emergence of collective outcomes. Two concepts are important here: attractors and attractor basins. Coleman *et al.* (2007, p. 1458) defined attractors as "a state or reliable pattern of change toward which a dynamical system evolves overtime and to which the system returns after it has changed." In generic terms, an attractor refers to a subset of potential states or patterns of change to which a system's behavior converges overtime. Robinson (2005) suggested that we can think about an attractor as the starting point of a system's dynamic behavior, an equilibrium state. For example, all supply chain actors are desirous of maintaining stability and performance in the face of disruptions. Attractors, in effect, represent the long-term dynamics of a system so that whatever the initial conditions, the system overtime gets "attracted" to the attractor in its basin (Goldstein, 2008). Basins of attraction can be likened to current system behavioral states. Attractors develop in dynamical systems in which the state of each element depends on, and is influenced by, the state of other elements much like CAS and supply chain networks. The concept of attractors has been used to study the long-term behavior of supply chains (Holstrom and Hameri, 1999). There are at least three management implications for SCRES from the properties of attractors.

First, the wider the basin of attraction, the greater the range of capabilities and options available to the actors. For example, supply chain actors can be encouraged to use flexible sourcing strategies such as supplier contract flexibility, adaptability strategies such as fast re-routing (Fiksel, 2003; Sheffi, 2005; Peck, 2005) to remain within a basin. Second, the depth of the basin of attraction provides an index of how difficult it will be for actors to adapt when faced with turbulence and supply chain vulnerability. Using a common ball and bowl heuristic favored in dynamic systems theory (Goldstein, 2008), if one tries to push a ball uphill out of a narrow basin, the ball will roll back to the basin in as soon as that effort is relaxed. If, however, there is sufficient push to dislodge the system from its current attractor state in a wider bowl, the system will gravitate toward another attractor. Finally, it may also be possible to build "desirable" attractors into the system as well as influence the attractor to which a system gravitates. As Seel (2008) noted, it may be possible to influence the nature of the attractor which the system "chooses" in social systems. For example, encouraging supply chain members to develop capabilities for flexibility, a culture of risk management and a greater ability for change would be tantamount to influencing the nature of an attractor.

Third, firms can use system-wide flexibility, not just strategic flexibility based on the choices of individual agents to enhance ecological resilience (Stevenson and Spring, 2007).

Flexibility reflects the ability of a system to respond rapidly to changes occurring inside and outside the system (Garavelli, 2003). Flexibility is both similar to, and can be an alternative to, redundancy. Supply chain actors have built product development, manufacturing, logistics and information system flexibility (Kumar *et al.*, 2006), common parts and modular designs (Pettit *et al.*, 2010; Christopher and Holweg, 2011) as means for managing disruptions. Sheffi (2005) described how Intel used flexibility effectively during the SARS scare that struck Asia in 2003. By building its fabrication plants to the same exact specifications, Intel was able to create interchangeable processes and fabrications throughout the world. Marchese *et al.* (2012) also reported that after the 2011 Japanese tsunami, companies with flexible manufacturing and supply chain capabilities generally recovered more rapidly than their non-flexible counterparts did. For the most part, the literature on flexibility has emphasized properties of individual actors, rather than system-level flexibility. However, both firm and system-wide or supplier network flexibility are important (Kumar *et al.*, 2006; Krajewski *et al.*, 2005).

Finally, a supply chain's capacity for ecological resilience can be promoted by building its adaptive capacity through adaptive management strategies. According to Walker *et al.* (2004), adaptive capacity involves "(1) making desirable basins of attraction wider and/or deeper, and shrinking undesirable basins (2) creating new desirable basins, or eliminating undesirable ones; and (3) changing the current state of the system so as to move either deeper into a desirable basin, or closer to the end of an undesirable one." Adaptive management provides a framework for learning about a system in a way that enhances the capacity for identifying and reducing uncertainty and surprise (Garmestani *et al.*, 2008). The goal of adaptive management is to build the capacity to reorganize the system within desired states in response to changing conditions and disturbing events (Walker *et al.*, 2004). A key part of adaptive management involves an iterative process of decision making, designed to identify and reduce uncertainty and surprise (Benson and Garmestani, 2011). At some level, adaptive management involves sense making (Weick, 1988), a process that allows managers to use information they get about the system to adapt to changing situations as management tries out interventions and learns what works and what does not (Garmestani *et al.*, 2008). Empowering all firms in a supply chain network to become co-owners and to make local decisions as they get new knowledge and information about the supply chain would go a long way in promoting the ecological resilience of the supply chain. Marchese *et al.* (2012) suggested that companies with resilient supply chains have clearly defined governance structures with clear accountability. In sum, ecological resilience promotes overall system response as it enables agents to adapt their response to disruptions. Therefore, the following is proposed:

P2a. Adaptive SCRES capabilities are positively associated with ecological resilience.

P2b. Ecological resilience is positively associated with system-wide persistence and recovery after a disruption.

P2c. Ecological resilience is a necessary, but not sufficient, condition for overall SCRES.

Evolutionary resilience

Once the long-term impact of a disruption has settled in, opportunities exist for supply chain members to evaluate whether the pre-disruption resilience of the network as a whole was satisfactory or not. It may become necessary to move the network to a new desirable state and that requires not just adaptive behavior but transformation. Indeed, adaptive strategies are relatively conservative, specific and local; they address a potential threat and vulnerability and adjust the system as a response to that threat. These strategies serve to maintain or return the system to the previous order or one similar to it (Redman, 2014).

Growth and movement to a better position post-disruption may require renewal and a set of capabilities more consistent with the third form of resilience: evolutionary resilience (Simmie and Martin, 2010).

Evolutionary resilience has been defined as the ability of a complex socio-ecological system to change, adapt and transform in response to stresses and strains, whether external or internal (Carpenter *et al.*, 2001). Based on that definition, a supply chain with evolutionary resilience is one that is able to transform to a new and better state after a disruption that pushes the system beyond its current threshold. Very few systems are likely to revert to their initial condition after a disruption and renewal may require a fundamental alteration of a system once the current conditions become untenable and undesirable (Walker *et al.*, 2004).

The presumption here is that such systems may not bounce back to what they were before an event but rather transform into a new system. Indeed, this conceptualization may have greater promise for our understanding of supply chain stability because unlike engineering and ecological resilience, the notion of a single equilibrium is rejected in favor of uncertainty, adaptability, transformation and how these intertwine in a dance of continuous change and instability. These descriptions seem more like the realities that supply chains face today. Evolutionary resilience may be more helpful in accounting for how supply chains transform into a "newer and improved state" following a disturbance because moving to an improved and newer position after a disruption entails more than adaptation; it may require transformation and resource reconfiguration (Ambulkar *et al.*, 2015). Transformation involves "potentially fundamental change and the strategy is to allow a system to reconfigure itself by introducing a new set of dynamics that operate within specified desirable values over a long term" (Redman, 2014, p. 2).

Evolutionary resilience is different from the two prior forms of resilience in three key respects. First, it challenges the notion of system equilibrium, something both engineering and ecological resilience accept. Second, and related, it accepts that systems may change without external disturbance and that change can happen because of internal stresses within the system itself. This is important given that most of the existing literature on SCRES seem to ascribe disruptions to external risk and disruption. Finally, in keeping with our conceptual framework, evolutionary resilience accepts that systems are "complex, nonlinear, self-organizing; they are permeated by uncertainty and discontinuities." (Berkes and Folke, 1998, p. 12). One similarity between ecological and evolutionary resilience is that human agency plays a key factor in the sense that actors can use purposeful behavior to manage resilience. Supply chain actors can use several strategies and capabilities to enhance evolutionary resilience (Olsson *et al.*, 2004).

First, social memory, the area in which captured knowledge about system change and adaptation is stored and subsequently used to deal with future change (Berkes *et al.*, 2002), is important. Social memory is important for linking past experiences with present and future policies (Westley, 2002). Past changes and the responses that were used are stored in the social memory of individual actors who, if they are in social networks, become repositories of knowledge that is then used during critical times in the system as a whole. In a supply chain, this points to the necessity of building multiple layers of relationships between key boundary people in firms within the supply chain. Second, trust, specifically goodwill based, among supply chain partners is important. When present, trust reduces risk, promotes collaboration, creates a sense of community and makes social life predictable (Cook, 2003). Existing research has shown that trust is an important social factor in determining agent behavior in CAS (Kim, 2009). Indeed, the presence of environmental uncertainty makes trust necessary (Iacobucci and Hibbard 1999), and trust has been mentioned as an important ingredient in supply chain relations (e.g. Ghosh and Fedorowicz, 2008; Sako, 1992). Building trust in networks requires investing in social capital. Social capital is made up of information, trust and norms of reciprocity inherent within social networks (Woolcock, 1998). Both social capital and trust have been identified as a glue for adaptive capacity (Adger, 2003) and social capital has been shown to strengthen supplier relationships (Uzzi, 1997).

Third, collaboration, the ability to work effectively with other firms, is another important tool for building a supply chain's capacity for growth and renewal (Pettit *et al.*, 2013). Collaboration allows actors to deal more effectively with major issues that sit within an inter-organizational domain, which may not be tackled by any organization acting alone (Vangen and Huxham, 2003). Collaboration builds a system's adaptive capacity (Folke *et al.*, 2005), facilitates the creation and sharing of knowledge in a supply chain (Christopher and Peck, 2004), encourages agents to support each other during a disruption (Jüttner and Maklan, 2011) or better avoid disruptions by sharing information, using joint decision making, aligning incentives and communicating collaboratively (Cao *et al.*, 2010). Sheffi (2005) reported that SEMATECH, a global consortium of semiconductor makers, created a Critical Materials Council (CMC) after a 1993 fire at a Sumitomo chemicals factory threatened 50 percent of the world's supply of an input used to encase silicon chips. The CMC has gone on to monitor such things as the impact of political instability in Zaire on the supply of cobalt. Fourth, and related, is informal networks. The building of informal networks can prove critical especially during times of rapid change, as networks will have the flexibility to share novel ideas rather quickly. As Kettl (2000) noted, informal social networks do not completely replace the accountability that exists within hierarchies, but complements them.

Fifth, individual and organizational learning is another important requirement for preparing for transformation (Folke *et al.*, 2005). CAS are capable of learning (Choi *et al.*, 2001; Pathak *et al.*, 2007). Agents in CAS learn by obtaining information from their relationships within the system as well as from the environment. The capacity for such learning allows the agents to modify their capabilities and change their schema to improve their fitness levels and performance (Tukamuhabwa *et al.*, 2015). Garmestani *et al.* (2014) noted that a key area of learning in CAS is to know what constitutes the critical thresholds of the system with the goal of preparing the system for adaptation and resilience. Learning on the part of each supply chain member is especially important since effective learning will improve their organization's capacity to take corrective action, as learning is important for dealing with ill-defined problems in dynamic systems (Nonaka and Takeuchi, 1995).

At the system level, learning that questions existing fundamental assumptions will prepare the system to adapt to new positions after a disruption. Ruhl *et al.* (2005) observed that processes that generate learning and knowledge of the dynamics of the system are useful in developing the social capacity for responding to change. Supply chain actors must engage in "double-loop learning" (Argyris, 2001) in which basic underlying assumptions, norms and objectives are questioned to stimulate new learning about the system after a disruption. Double-loop learning requires a new mental model as old assumptions are rigorously challenged. It also enables a system to identify whether its mission and principles are still appropriate under the current circumstances. This should be especially important in supply chain management since the actors may need to question some of their old models about resilience. Prior research has, in fact, documented that organizational learning enhances SCRES by aiding adaptation and through modifying resilience strategies (Ponomarov and Holcomb, 2009; Pettit *et al.*, 2010).

Leaders can help trust building, system learning and provide the impetus for system-wide collaboration. Visionary leaders in supply chains networks have the capacity to overcome contradictions, create new syntheses and change people's mindsets to be more in tune with the new reality after a disruption (Westley, 2002). Leaders who adopt what Kim and Mauborgne (2003) called "tipping point leadership" may be particularly effective when there is the need for a transformation in the supply chain network after a disruption.

The theory hinges on the insight that in any organization, fundamental changes can occur quickly when the beliefs and energies of a critical mass of people create an epidemic movement toward an idea. Tipping point leaders overcome the resource, cognitive and political hurdles that often frustrate change and renewal. Therefore, the following is proposed:

P3a. Collaborative SCRES elements will be positively associated with evolutionary resilience.

P3b. Evolutionary resilience will be positively associated with supply chain transformation and growth.

P3c. Evolutionary resilience is a necessary, but not sufficient, condition for overall SCRES.

Managing resilience: integrating resilience types and supply chain resilience

The three resilience types presented in the conceptual framework are not mutually exclusive because several of their antecedents are interrelated. For example, constructs such as efficiency and agility are related, while redundancy and collaboration may be implying behaviors that are contrary to efficiency and some key capabilities identified may in fact complement each other. Clearly, there are synergies and tradeoffs as we combine resilience types to manage the overall resilience of a supply chain.

A resilient supply chain must have the capacity to manage both the pre-disruption and post-disruption phases, including the possibilities for renewal and growth. In an ideal situation, it would be best for supply chains to have all the resilience capabilities we discussed. However, the discussion so far suggests that certain types of resilience may be achieved at the expense of others. There are some incompatibilities and possibilities for complementarity among and between the resilience types. For example, redundancy is a tool for fostering adaptation and ecological resilience but has inefficiencies. The challenge then is how to negotiate the inevitable tradeoffs inherent in these resilience types as well as explore the possible synergies in combining them.

First, there may be synergies in combining engineering and ecological resilience. A supply chain that is efficient and has contingency plans may be better placed to meet customer demands and reduce loss in the event of a disruption. Recovery is especially important since customer needs and business demands still need to be met even with a disruption. For example, the use of buffer stock may be the best way of managing a disruption. More important, a supply chain that is designed for quick recovery has a better chance of using adaptive behaviors and system-wide coordination to develop response strategies in the event of a disruption. A supply chain with a weak recovery capacity and, by implication, lower business and customer fulfillment during a disruption is less likely to promote system-wide collaboration and recovery.

Second, we can design supply chains to balance the tradeoff between efficiency and redundancy (Christopher and Peck, 2004). For example, we can manage SCRES by determining when each resilience type is most likely to work in promoting recovery and response. For example, engineering resilience may be a preferred option when the environment is stable enough for the actors to predict changes in system behavior or when they can control both internal and external sources of variability. Satisfying both conditions is challenging but not impossible to do. For example, the CMC of the global semiconductor manufacturers mentioned earlier monitors all the different facets of semiconductor and electronic supply chains. The council goes as far as examining shifting patterns of R&D investment and capital expenditures to understand future material supply needs and works to develop alternative sources of supply. The council is known to carefully monitor and collect monitoring data including political instability in supplier countries (Sheffi, 2005). This sort of intimate and detailed knowledge about a supply chain may favor optimization approaches.

Of course, there are limits to the adequacy of engineering resilience even under those circumstances and these have been explained elsewhere in the paper. For, it is not if but when a disruption that eventually breaks a system's resistance occurs and engineering resilience would not be enough. To recap those arguments briefly, supply chains designed to keep costs low in stable business environments can increase risk during disruptions (Fiksel *et al.*, 2015) and it is not always easy to do the risk assessments and predictions upon which engineering resilience depends. Ecological resilience becomes more useful when prediction is low and our ability to control variable sources of disruption low and building flexibility into such a system would be helpful. Indeed, applying the ecological strategies discussed earlier, such as flexibility and system redundancy, allows such a system to safeguard itself against catastrophic failure when the system's resistance is broken. Flexibility allows supply chains to more easily deploy alternatives during a disruption (Pettit *et al.*, 2013) and managing disruptions in all tiers of a supply chain clearly requires coordinated behavior and the deployment of adaptive behavior.

Third, there are tradeoffs that need to be made between ecological and engineering resilience because some aspects of efficiency and ecological resilience are incompatible. For example, response diversity strategies such as functional redundancy are important qualities of adaptive behavior. In fact, keeping an inventory buffer may be one of the best ways of meeting demand during a disruption (Sheffi, 2005). However, redundancy includes waste as it may involve duplication of capacity. Indeed, redundancy may be an expensive means for building SCRES (Christopher and Rutherford, 2004). Worse yet, unless there is a crisis, the transaction cost of response diversity may increase substantially. At the same time, ecological resilience may also come at the cost of efficiency because ecological resilience requires inter-organizational coordination with the risk of increasing interdependence and greater risk to the supply chain. Supply chain collaboration can cause conflict or lead to increased risk through greater interdependence and the sharing of sensitive information (Jüttner and Maklan, 2011). Of course, the risks associated with interdependence may be mitigated in the presence of trusting relations. Like engineering resilience, ecological resilience has its limits. Walker *et al.* (2009) suggested that an overly strong focus on adaptability can undermine the overall resilience of a complex system by optimizing the system to adapt to a particular set of disruptions but in so doing decrease resilience to other unknown sources of disruption, suggesting again that there are limits when it comes to ecological resilience.

Finally, as Fiksel *et al.* (2015) observed, supply chains actors need to realize that every disruption represents a learning opportunity that may suggest shifting to a different state of operations. However, transformation is only possible when the supply chain is able to recover and respond to any disruption. Since both ecological and engineering resilience have some limits and some disruptions may require system-wide change or transformation and renewal, evolutionary resilience becomes a necessity. Building evolutionary resilience may require a mindset change because both engineering and ecological resilience accept a single equilibrium as a desirable state of a system. Practically what that means is that firms which have invested resources on developing several forms of resilience capabilities may find it difficult to drastically alter their previous behavior and adopt new behaviors. Yet, no system ever reverts to its status *quo-ante* after a disruption. Supply chains that have a capacity for recovery and adaptive response are more able to engage in transformative behavior than those unable to maintain their existence long enough to begin the processes of transformation. Evolutionary resilience broadens engineering and ecological resilience to incorporate the dynamic interplay of persistence, adaptability and transformation across multiple scales and timeframes (Holling and Gunderson., 2002; Folke *et al.*, 2010). In the end, firms need all the three forms of resilience. Engineering resilience enables the actors to recover quickly from disruptions but sustaining that response requires collective behavior adjustment by other members in the supply chain and the need to develop collective decisions that can contain the disruption. No individual actor may be able to contain a disruption all by himself or herself. Ecological resilience assures that the supply chain can adjust and manage disruptions so the system can recover. Evolutionary resilience becomes important in the face of change and renewal. To sum up, an ability to deploy recovery strategies quickly improves the chances for system-wide adaptation. Even as the agents engage in adaptive behavior, they still need to meet customer needs and so response capabilities are important. Unless the agents can respond and recover, it may not be easy for them to engage in transformation. More importantly, a failure to transform after a severe disruption means that the supply chain cannot move to a new fitness level. The preceding discussion is the basis for the following propositions:

P4. SCRES is a multidimensional construct: SCRES is composed of engineering, ecological and evolutionary resilience.

P5. Engineering resilience strengthens both ecological and evolutionary resilience. The ability for quick recovery allows for greater system-wide adaptation and renewal in response to supply chain disruption.

P6. Ecological resilience strengthens both engineering and evolutionary resilience thereby facilitating recovery, response and transformation after a disruption. Supply chains with adaptive capacity will show greater recovery and ultimately renewal capacity since adaptation cushions both recovery and transformative behaviors.

P7. Evolutionary resilience strengthens both engineering and ecological resilience by linking persistence, adaptability and transformation across periods.

P8. A combination of engineering, ecological and evolutionary resilience enhances SCRES (defined as the supply chain's capacity to respond, recover and grow after a disruption) than either resilience type alone.

Conclusions

A resilient supply chain may be able to withstand one set of disruptions and fall vulnerable to a different set of disruptions for which it is not prepared. The dynamic and evolutionary nature of supply chains requires actors to focus on all the three types of resilience: engineering, ecological and evolutionary. It is important to recognize that efficiency, adaptation and transformation may all be needed for long-term supply chain performance. One implication of that recognition is that firms need to develop multiple capabilities to manage supply chain risk and reduce vulnerability to disruptions. Actors should not rely on just one resilience form for risk management as each has its own limitations. For example, engineering resilience approaches that rely on risk assessment, mitigation and monitoring alone may lure firms into a false sense of security. At the same time, adaptive resilience has its own limits, and the knowledge that all disruption opens up an opportunity for learning and transformation is important.

Managerial implications

This research has several implications for managers. First, it is important for managers to develop new mindsets about how they manage supply chains (Christopher and Holweg, 2011). A CAS perspective shows us that supply chains are dynamic systems that are subject to continuous change and evolution. Such mindset change amounts to a reframing of perspectives about supply chain stability. As Westley and Antadze (2010) put it, reframing involves seeing a situation in a new and different way that often enables new possibilities to emerge. This mindset change is required in three areas: first, the need to embrace volatility as a permanent feature of supply chains because these systems may never be at a standstill, but rather will be changing in nonlinear ways. Supply chain actors must be prepared for adaptation by embracing change and surprise. Indeed, strategic adaptation may be more important than planning for resilience alone. Second, understanding the nature and impact of turbulence and third, the way actors see crisis needs to change because crisis in CAS often presents opportunities for renewal and it seems some firms are yet to appreciate the need for learning these lessons. For example, Sheffi (2005) observed that even after such wide-reaching disruptive events such as "9/11" and Hurricane Katrina, most companies are still not thinking systematically about managing supply chain risks and vulnerabilities. Second and related, there is the need to foster CAS thinking among stakeholders in the supply chain. Complex adaptive thinking means accepting unpredictability and uncertainty as realities of supply chain evolution. Walker and Salt (2006) observed that even though CAS thinking alone would not promote resilience, the recognition that such systems are based on connectivity, interdependence and uncertainty may be a first critical step toward management actions that foster system resilience. Finally, the lesson from CAS is that it would not be easy to design any fail-proof blueprint for performance in supply chains and actors may be better off carefully monitoring the system and making adaptations if and when they become necessary (Axelrod and Cohen, 2000).

Implications for research

This research has several theoretical implications. There is a need to explore the multidimensional nature of resilience further. The idea that resilience may vary across time and space is intriguing and requires further theoretical and empirical exploration. There are issues on how we design research to explore supply chains as CAS. Pathak *et al.* (2007) summarized the unique research design issues that confront the use of the CAS-based research in general and those recommendations are still useful. These include the unit of analysis, measurement and methodologies for studying complex supply chain networks. With regard to measuring SCRES, there is a need to test broader models of resilience since it is a multidimensional construct. Level of analysis issues are also important since as a system, the appropriate level of analysis for studying SCRES is the system, not firm level, if we are to avoid model misspecifications (Klein *et al.*, 1994). Researchers will do well to use dynamic theories such as CAS since the structure of supply chains are dynamic by nature. This paper has provided a multidimensional framework for SCRES and extended our existing understanding of SCRES. Additional refinements and empirical testing of the propositional inventory generated here will help extend our understanding of how best to manage supply chains for their long-term stability and performance.

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