

Berger, Ron; Wagner, Ralf; Dion, Paul M.; Matthias, Olga

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# Disrupting disruptions: enhancing supply chain resilience—lessons from the US Air Force

Ron Berger<sup>1</sup> · Ralf Wagner<sup>2</sup> · Paul M. Dion<sup>3</sup> · Olga Matthias<sup>4</sup>

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## Abstract

Black swan events have highlighted the importance of supply chain resilience and hence drawn increased attention from academia. Using military supply chains as our research setting, we illustrate how supply chain resilience can be implemented in civilian networks and incorporate agility and flexibility into a responsive system-to-system model. We use a simulation model based on the Cassandra application to further develop supply chain network resilience theory. Our model provides updated situational awareness to decision makers and allows managers to identify direct and indirect threats to supply chains, allowing adaptation to unforeseen situations. We developed a dynamic, whole-system network model to provide timely, accurate, updateable and scalable information to planners and decision-makers at all levels in-order to reduce risk and increase resilience.

**Keywords** Supply chain resilience · Complex adaptive systems · Casandra · Modeling · Disruption

## 1 Introduction

On March 11, 2020, the World Health Organization declared the COVID-19 outbreak a pandemic. Pandemics are defined as the occurrence of an infectious disease over an extensive area, crossing international borders, and affecting a great number of individuals (Kelly, 2011).

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✉ Ron Berger  
ron.berger@biu.ac.il

Ralf Wagner  
wagner@wirtschaft.uni-kassel.de

Paul M. Dion  
pdion3@unl.edu

Olga Matthias  
olga.matthias@capabilitygap.com

<sup>1</sup> Graduate School of Business Administration, Bar-Ilan University, Ramat-Gan, Israel

<sup>2</sup> School of Economics and Management, University of Kassel, Kassel, Germany

<sup>3</sup> College of Business, University of Nebraska Lincoln, Lincoln, USA

<sup>4</sup> Business School, Heriot-Watt University, Edinburgh, Scotland

Pandemics are characterized by a reduced ability to predict the future and a perceived loss of control. They represent situations where responses to the emergency generate additional unforeseen (and usually negative) outcomes (Gebhardt et al., 2022). A pandemic-induced crisis is a heterogeneous phenomenon, varying in breadth (what is affected), depth (intensity of its impact), and temporality (duration). The present global economic crisis strongly linked to the COVID-19 pandemic is substantially different from the last financial crisis (2007–2008) since it does not have a financial origin (bubble–burst cycle). It can be viewed as a black swan event—a totally unexpected event that takes the world economy by surprise (Belghitar et al., 2022). Black swan events occur with low probability but have high impact and are perceived by critical stakeholders to threaten the viability of the economy (Puthusserry et al., 2022). In the COVID-19 black swan event, this unforeseen development meant a simultaneous supply and demand shock that was difficult to overcome (Amankwah-Amoah et al., 2021). For instance, on the supply side, employees were unable to go to work, production was severely disrupted and supply channels were blocked; on the demand side, the shock was manifested by households and businesses being unable to buy basic goods and services as a result of lockdowns and supply chain disruptions (Sarkar & Clegg, 2021). The COVID-19 crisis was characterized by complexity and uncertainty, influencing (and being influenced by) government policies, health systems, firm behavior, and individual behaviors (Mena et al., 2022).

These black swan events energized the present research into supply chain resilience, the ability to respond to and recover from unexpected supply chain disruptions (Brandon-Jones et al., 2014; Hohenstein et al., 2015). This paper focuses on supply chain resilience modeling and not environmental trigger events. According to Tukamuhabwa et al. (2015) and DuHadway et al. (2017), supply chain resilience can be deconstructed into phases encompassing anticipation, resistance, and recovery. Academic research focused on developing strong resilience strategies for better coping with disruptions (Gebhardt et al., 2022; Kamalahmadi et al., 2022; Verma & Gustafsson, 2020). The operational and economic global disruptions seen during the COVID-19 period of 2020–2023 amply demonstrate the vulnerability of supply chains to idiosyncrasies of demand and supply shocks. Researchers note that lack of supply chain resilience was a primary reason for poor supply chain performance during this period (Qader et al., 2022). The impact caused by the COVID-19 pandemic on global trade is without precedent, precluding the application of traditional theories of risk and resilience (Mena et al., 2022).

It does not, however, take a black swan event to underscore the vulnerability of supply chain to disruptions. These are unavoidable in today's economic environments and varied in cause and effect (DuHadway et al., 2019; Gebhardt et al., 2022). Over the last few decades, corporations have set up global supply chains by expanding offshoring and outsourcing activities (Gebhardt et al., 2022). Globalization has led to supply chains becoming longer and more complex, thereby increasing their vulnerability to shocks (Mena et al., 2022). Risk, in this context, relates to events that can cause widespread and sustained shortage of a product or service with no alternatives or substitutes available. International supply chains continue to expand in line with increasing levels of globalization, leading to higher interconnectedness and interdependence among firms. While the interdependence has enhanced supply chain efficiency with practices of lean manufacturing, concurrent engineering, and “just-in-time” deliveries, it has also increased supply chain vulnerabilities (World Economic Forum, 2019). The economic and social connections that engendered globalization have also reinforced interdependencies and hence the need for improved resilience.

Complex adaptive systems were initially applied to researching living systems (Surana et al., 2005). These systems are defined as a kind of structure that gradually emerges as a

coherent form through the properties of adaptation and self-organization (Choi et al., 2001). It focuses on the emergence of order in dynamic and non-linear systems (Kauffman, 1995). Resilience is one major inherent feature of complex adaptive systems (Fangxu et al., 2024). To function as a complex adaptive system, one connects with others in the system and make decisions based on imperfect information (Day, 2014). Co-evolution may instigate a change from equilibrium to disequilibrium between a system and its environment. As organizations adapt to complex environments with multiple relationships and interactions, more and more scholars and practitioners suggest that it is a natural step to investigate operations and management issues within the complex adaptive systems paradigm (Pathak et al., 2007). By utilizing complex adaptive systems theory, we are able to develop a detailed analysis of the key tenets of complexity from which we provide theoretical and practical insights.

Supply chains are human constructs with functional goals that include delivering specific products and services to customers with set cost minimizing or profit-maximizing objectives (Novak et al., 2021). Supply chains have been conceptualized as complex adaptive systems that operate as networks (Choi et al., 2001; Pathak et al., 2007) or as complex socio-ecological systems that are cross-linked to other social-ecological systems that can shape what is considered normal and desirable (Yaroson et al., 2021). From a complex adaptive system perspective, the supply chain continuously adapts, self-organizes, and transforms into new configurations that allow it to maintain its functionality (Hearnshaw & Wilson, 2013; Mason & Leek, 2008; Novak et al., 2021). Accordingly, supply resilience and risk management's joint aim is to abate the influence of sudden disruptions and return to operational normality in a timely and cost-effective manner (Christopher & Holweg, 2017). As such, we must understand the sources of such disruptions.

Supply chain disruptions have many causes, which we classify into five main groups. The first cause is the demand and supply shocks that occur when there are unexpected increases in demand or supply shortages. These temporal mismatches occur when resources are consumed at rates that cannot be sustained or even at a normal rate when there is not enough supply in sight. For example, harvesting lumber or fish more rapidly than a forest or fish populations can naturally regenerate or when the COVID-19 epidemic drove up lumber prices when producers completely misgauged the number of homeowners doing renovations during the pandemic (NBC News, 2021). Another example is the US military now facing ammunition shortages because of a demand surge caused by the Ukraine invasion (WSJ, 2022). In the US, vehicle sales collapsed during COVID-19 and then rebounded but chipmakers had meanwhile switched to supplying consumer electronics makers, causing shortages and delays. The switch was a conscious decision by chipmakers responding to the market that resulted in automakers not being able to meet market demand (Feltmate, 2021).

The second source of disruptions is natural disasters that can wreak havoc on supply chain systems. For instance, in 2022 Hurricane Ian left Florida with shortages ranging from bottled water to flashlights (Tampa Bay Times, 2022). Following the Tohoku earthquake in Japan in 2011, Toyota's supply chains were severely disrupted and, as a result, the company put in place-improved coordination mechanisms to restore supply chain resilience (Matsuo, 2015).

The third source of disruptions is deliberate political and military conflicts, potent sources of supply chain disruption (Blessley & Mudambi, 2022). For instance, Russia's invasion of Ukraine in February 2022 set off a domino effect of supply chain disruptions too numerous to catalog, shaking the core of global business. It is claimed that the Kremlin set out deliberately to cause economic disruption among NATO supporters of Ukraine (Rannane et al., 2022).

The fourth source of disruptions is unintentional accidents (Roh et al., 2021). For instance, the *Ever Given*, which ran aground in the Suez Canal, left more than 100 ships stranded at each end of the canal for weeks, leading to global delays and supply disruptions.

The fifth source of disruptions is interactions between causes one through four (Gunasekaran et al., 2015; Hearnshaw & Wilson, 2013). For instance, high fuel prices in Florida caused by the Russian invasion of Ukraine (February 2022) were exacerbated by the natural disaster in Florida (September 2022), which made the resupply of gas stations difficult. Both supply and demand chain vulnerabilities fed one another leading to acute shortages. In another example, COVID-19 caused a shortage of microchips because workers could not get to the fabrication plants or were too sick to come to work, which situation was worsened by the Ukraine war, which increased demand for chips as components in weapons.

The risk of supply chain disruption can be further intensified by managerial factors when two industrial practices—lean manufacturing and just-in-time production—are followed (Yarosan et al., 2021). These approaches aim to eradicate possible waste and advance the flow within the supply chain and suppliers' responsiveness to customers. Nonetheless, corporations could become more susceptible to supply chain disturbances when adopting these strategies. To successfully follow them, corporations must depend on actors outside of their control (Craighead et al., 2020), which paradoxically weakens their supply chain resiliency. To reduce such dependency, redundancies may be necessary. These may sacrifice the efficiency goals of individual firms in the short term, but promote supply chain resilience over the long term. Nandi et al. (2020) claim that effectively managing supply chain resilience is more significant than honing internal competences. This issue has yet to be fully explored.

Supply chains require managerial strategic interventions to survive disruptions. This can be done, in part, by modeling possible solutions to potential problems (i.e., a type of risk analysis and management). Here we ask and model how resilience can be enhanced by reducing asset specificity. Much of the contemporary supply chain management literature researches resilience from the perspective of a firm or a specific industry (Novak et al., 2021). In our view there is a need to improve the understanding of the linkages between resilience and the multiscale dynamics that explain how supply chains evolve over time in light of environmental changes, as discussed in the previous paragraphs about trigger events (Gebhardt et al., 2022; van Hoek, 2020; Verma & Gustafsson, 2020). We seek to create a holistic simulation model that would help managers in creating a complex adaptive system that is better able to cope with disruptions to the supply chain in advance or in real time. It would provide alternatives that facilitate speedy decisions about optimum choices for continuous information and supply flows. It will further help to maximize supply chain management robustness. We contribute to existing research models on supply chain management by identifying the factors that enhance supply chain resilience in environments that are prone to disruption.

We evaluate key factors that can influence both the robustness and responsiveness of the supply chain network using experiences from the US Air Force. Our paper offers an empirical study of a dynamic system designed with a complex adaptive system network applied to a perennial military problem as well as proof of its efficacy. Such military findings were found to be applicable in civilian supply chains seeking enhanced supply chain resilience (Kakhki et al., 2022). The paper describes a project conducted with the United States Air force in which supply network resilience modeling was applied to its supply chain. The United States Air Force sought solutions to problems caused by insufficient management of supply chains, which in turn led to flawed decision-making, based on partial information, continuing poor tracking and a defective data cycle. This research is the first exploration, to the best of our knowledge, of a complete supply chain model as a series of interdependent networks. This

study addresses proactive designs of supply chains including the factors that could impinge on supply chain performance and resilience.

Military forces have increasingly been deployed in humanitarian assistance and disaster relief. This pulls on the military's strength of 'readiness' to help peacekeeping and disaster relief activities. On the other hand, it is hampered by the different working styles, roles and guiding principles the military and humanitarian organizations have (Heaslip & Barber, 2016). The large number of agents involved in the network further increases complexity. These specific performance challenges make military supply chains particularly suitable for whole-chain analysis using a networked approach to coordination and decision-making. Yoho et al. (2013) posit that defense and business supply chains have become similar because supply chain turbulence has generally increased, as has the imperative to have an efficient and effective flow of goods, services and information.

The remainder of the paper is organized as follows. First, we examine previous research on supply chain resilience in light of black swan events. Secondly, we explain the research methodology implemented. Thirdly, we present our model and results, and discuss their implications in a non-military context. Lastly, we derive conclusions and implications for theory and practice, note limitations, and propose future research directions.

## 2 Literature review

Resilience is reflected in the ability to prepare for and recover from low probability but recognized disruptive events and achieve some post-disruption operational equilibrium (Dolgui et al., 2018). Resilience focuses on maintaining system functionality as opposed to maintaining functional efficiency (Slack et al., 2009). Being resilient, the system is stable, near equilibrium or steady state, and able to return to that state following shocks, with more resilient systems bouncing back more quickly than less resilient systems.

The resource-based view (Brandon-Jones et al., 2014), dynamic capability theory (Chowdhury & Quaddus, 2017a, 2017b; Iftikhar et al., 2021), resource dependency theory (Gebhard et al., 2022), social exchange theory (Shin & Park, 2021), and system theory (Kim et al., 2015) have been widely used as theoretical bases for supply chain resilience research but all have been found to possess significant shortcomings (Tukamuhabwa et al., 2015). These theories focus on the internal workings of supply chain resilience, without taking supplier systems and co-evolution into account. Where these papers do acknowledge a systemic aspect, it tends to be static in nature. For instance, resource based view is firm biased and ignores component synergies (Gebhard et al., 2022). It assumes predictable environments where the future value of resources is determinable. Dynamic capability models based on inter-firm components (Wang & Ahmed, 2007) fail to address supply chain resilience as a whole ecosystem. Systems theory does recognize the systemic structure of supply chains but in focusing on flows, flow units and their sources, omits temporal changes, which reduces supply chain resilience accuracy and ability to forecast complex adaptive system future events (Choi et al., 2001; Kim et al., 2015). Furthermore, the bulk of research on supply chain resilience was found to be conceptual in nature (Wieland et al., 2016; Christopher & Holweg, 2017; DuHadway et al., 2017). Teece et al. (1997) extend the resource based theory and believed that firms need to constantly integrate and reconstruct their resources and capabilities, as they have to cope with changes in the external market environment and avoid losing their competitive advantage due to these changes. The theory is suitable for clarifying how a firm improves its operational performance by manipulating the right resources. Some research has been done

on modeling of supply chain resilience (Erol et al., 2010), complex adaptive system studies (Brandon-Jones et al., 2014; Purvis et al., 2016) and survey-based work (Wieland & Wallenburg, 2013). It seems to us that such examinations fall short of addressing network issues, which align with biological ecosystem analogies. Accordingly, new model conceptions are needed.

Industrial ecologists look to biological ecosystems as analogies or metaphors in the study of supply chains (Côté, 1999). Some ecologists argue that it is the diverse nature of an ecosystem, which is central to its sustainability. This diversity enables some redundancy in function, which, in turn, supports the stability and resilience of the system. Scholars have used biological ecosystems as an analogy to explore inter-organizational relationships and supply chains, yet the prevalence and increasing importance of business ecosystems across industries has sparked a burgeoning research focus in this area. Allenby and Cooper (1994) pointed out that supply chains share many of the properties of biological systems. Their conclusion was that a supply chain resembles a biological community.

Despite resource-based view's deficiencies, in our view, it is the best starting point to apply to our model as it is based on the idea that companies depend on their environments to acquire scarce resources under favorable conditions to ensure their survival (Nandi et al., 2020). Moreover, given that resilience research is mostly based on resource-based view, it would seem a suitable framework for studying supply chain interdependencies (Spieske et al., 2022) with biological ecosystem analogies to offset the above-mentioned theories' weaknesses. Resource-based view deals with conditions where supply chains depend on an uncertain environment to acquire resources essential for their operations. Using resource-based view, prior literature has shown that firms' internal resources, such as physical facilities, financial assets, human resources, and technological development as well as their external resources such as supply connectivity, are critical for supply chain resilience (Gebhardt et al., 2022). Resource-based view states that a firm's competitive edge is influenced by the strategic resources or capabilities it possesses (Barney, 1991). The basic premise behind this view is that resources are heterogeneously and spread across firms. If they are valuable, rare, not perfectly imitable and non-substitutable, they are able to sustain the firm's competitive advantage (Iftikharet al., 2021).

Resilience from a resource based view perspective is an outcome of the organizational capabilities employed to minimize the unfavorable impact of disturbances (Nandi et al., 2020). Resilience is considered a multifaceted concept that addresses how an organization and its members react to uncertainty (Blessley & Mudambi, 2022). These are all-inclusive capabilities, which are utilized to obtain resources, and reorganize, integrate, and prioritize their allocation in a complex business environment. This implies that a resilient supply chain possesses large buffering capacity, and an even more resilient supply chain is one that can withstand relatively large shocks while retaining its current structures and processes (Kamalahmadi et al., 2022). Resilience-building strategies allow the supply chain to maintain functionality by adapting and transforming in response to black swan events. For example, if a set of suppliers is no longer available due to an embargo or a natural disaster, a bridging strategy, which only resilient supply chain management would have, might involve the improvisation of actively managing customer expectations, using new suppliers, or finding substitute inputs.

To use resource-based view and limit the impact of its shortcomings, we view the supply chain as one intertwined unit and not as individual firms. By integrating and exploiting resources across autonomous firms, new exclusive competences are formed and resilience increased (Lu et al., 2010). In other words, learning from past research on resource-based view's flaws, we expand its theoretical scope to focus on the supply chain, not on a specific



firm, and introduce unpredictable environments into our model, which is able to adapt to disruptions. Supply chain integration is realized in the resilience literature as a strategic resource that can be utilized in alleviating supply chain disruptions and enhancing resilience (Wu et al., 2010). It is claimed that a resilient supply chain is a network that can retain existing structures and functions should it undergo some type of shock (Novak et al., 2021).

The resource dependency theory, furthering the resource based view, introduced by Pfeffer and Salancik (1978) is an organizational theory that focuses on how organizations rely on others and manage their relationships to survive by reducing environmental uncertainty. This theory is the main motivator in creating a value chain network (Barringer & Harrison, 2000). The theory can enlighten the antecedent of inter-organizational collaboration and the reason for joint actions. It views organizations as the stakeholders, which have dynamic interests and can be used to examine and interpret their behavior in collaborating with others for achieving their goals. Within this theory, organizations are aware that dependence forms trust and tolerance of others, which becomes the basis of a relationship.

However, both the resource based theory and the resource dependency theory focus on resource potential rather than systemic interactions, which limits its explanatory power regarding the relationship between visibility and business performance (Wong & Karia, 2010). In the field of supply chain research, the resource-based view focuses on the internal resources of firms and does not go beyond the level of firms (Kraaijenbrink et al., 2010). In addition, the resource-based view assumes that the future value of resources is determined in a predictable environment, but supply chain resilience is precisely nonlinear, dynamic, and unpredictable.

To overcome the shortcomings of the resource based theory and the resource dependency theory, Wang et al., (2016) introduce the dynamic capability theory, as an extension to the resource based theory. It better explains the influence of big data capability. Many studies have explored supply chain resilience and its formation mechanism based on dynamic capability theory, and many researchers regard supply chain resilience itself as a dynamic capability (Chowdhury & Quaddus, 2017a, 2017b; Kraaijenbrink et al., 2010). As such, the dynamic capability theory provides a theoretical basis for related research on supply chain resilience and the logical framework of this paper. Common to these studies is that dynamic capabilities are distinct from ordinary routines or organizational competences, and even dynamic capabilities are hierarchically ordered in ways that the higher-order capabilities contribute the most to adaptation after radical changes (Winter, 2003). By considering dynamic capabilities as best practices, these authors render the concept of dynamic capabilities more practical and generalizable (Eisenhardt & Martin, 2000).

As systems provides an essential, actionable framework from a managerial perspective, we utilize in parallel to the dynamic capability theory, systems theory. The reason for selecting this systems-level approach is that it provides an appropriate theoretical view for generating and guiding informative decision insights to supply chain actors in risky environments, ultimately enhancing the overall network resilience (Govindan & Al-Ansari, 2019). Spiegler et al. (2012), among others, have studied the dynamics of supply chain systems and assessed alternative inventory and ordering control policies against resilience, having a view on a specific process, thus providing a demonstration of the usefulness of system thinking as a way to link resilience and supply chain operations.

Social exchange theory was also used in supply chain research. It focuses on relationships that inherently involve an exchange between providers and consumers (Berger et al., 2014). Borrowing its roots from social psychology and behavioral economic paradigm, the premise of this theory asserts that, when an actor is being presented with choices, they will undergo subjective cost–benefit analysis and weight available alternatives before making the final



decision. Cropanzano et al., (2017) concluded that this theory is about individuals as part of a community and how they make rational decisions to maximize positive experiences through social interactions. Social exchange theory posits that reinforcement mechanisms underpin social relations, arguing that people engage in social exchanges where mutual benefits form the basis for maintaining these relationships. A basic assumption is that the exchange parties do not seek a one-off transactional relationship but a continuous social relationship. As this theory is more on a personal level and not on the supply chain technical level, we found that this theory does not fit the focus of our research.

Prior research on supply chain resilience seldom considered it in terms of interdependent networks or whole system solutions (Hearnshaw & Wilson, 2013). This linearity precludes supply chain resilience from handling the vagaries of disruption in today's dynamic supply chain – so essential when a black swan event occurs (Oliveres-Aguila & Vital-Soto, 2021). Supply chain models are often found to be unrealistically oversimplified and linear (Hearnshaw & Wilson, 2013; Kamalahmadi et al., 2022; López & Ishizaka, 2019), which inhibits efforts to boost supply chain resilience. Many researchers have come to the conclusion that supply chain resilience analysis based on simplistic linear scrutiny is ineffective and lead to supply chain resilience failures (Li & Zobel, 2020; Oliveres-Aguila & Vital-Soto, 2021).

Researchers have begun re-conceptualizing supply chains as dynamically evolving structures with diverse connections and multiple constituent entities. This new view requires new models and theories to depict the complex and adaptive phenomena that may affect resilience (Hearnshaw & Wilson, 2013; Tukamuhabwa et al., 2015). The focus has moved to consolidating results from linear quantitative network modeling and optimization (Ribeiro & Barbosa-Povoa, 2018; Scholten et al., 2019) and concepts describing human behavior (Oshio et al., 2018) and management techniques (Linnenluecke et al., 2015). Tukamuhabwa et al. (2015) offered one of the first research efforts on supply chain resilience by taking a nonlinear complex adaptive system approach (Holland, 1992). Their research highlighted a number of gaps in the existing approaches to making supply chains consistently resilient. For instance, they pointed out that interdependencies between global supply chains alongside their individual sources need to be considered and, in addition to strategies to increase supply chain resilience; the implementation of these strategies needs to be addressed.

Recently, Mena et al. (2022) classified supply chain resilience according to adaption capabilities ranging from individuals and single supply chain systems up to economies and societies on a national level. Complementing this research, Gebhard et al. (2022) introduced a distinction between studies considering response measures and recovery measures to a supply chain disruption post hoc. Parker and Ameen (2018) proposed a resilient adaptive system design that, on the one hand, is robust to disruptions without accelerating buffering and, on the other hand, prevents stock-keeping costs from rising. More and more, supply chains are being viewed as having the complexity of nonlinear biological systems (Shin & Park, 2021). Like biological systems, supply chains rely on relationships, reciprocity, and coordinative capacity and function best as a mutually beneficial shared enterprise (Dooley et al., 2013; Qian et al., 2021; Tangpong et al., 2014). Hence, a supply chain resilience model must account for the necessity of a post-disruption channel function (possibly at a diminished level) in acute situations such as military or disaster relief applications (Kamalahmadi et al., 2022). The issue, however, of continued operation at a diminished but still viable functioning level when a distribution actor is lost is not well researched (Gebhardt et al., 2022). Complex adaptive systems theory, proposed by Holland (1992), builds on general systems theory (Holweg & Pil, 2008). It is concerned with the total performance of a system rather than its separate parts, even when a change in only one or a few of its parts is contemplated (Ackoff, 1971). It

is applied in many disciplines, including evolutionary biology, sociology and management systems (Choi et al., 2001; Holweg & Pil, 2008).

System properties develop from the associations between the system parts, how they interact, and how they fit together. Complex adaptive system theory allows the study of the behavior and response of systems that dynamically change and learn from experience. Complex adaptive systems form an interconnected network of entities, which over time, coalesce into a coherent system because of their ability to adapt and self-organize. This implies flexibility, responsiveness, and a learning capability, partly due to the fact that the entities that constitute the complex adaptive systems are guided by order-generating rules, called schemas (Choi et al., 2001; Pathak et al., 2007). In the context of supply chain resilience, flexibility is defined as the aptitude to quickly adapt and react to disruptions instead of trying to withstand the disturbance (Dolgui et al., 2018). It has been asserted that a supply chain looks like a complex adaptive system (Choi et al., 2001; Hearnshaw & Wilson, 2013; Day, 2012), since it mirrors the main features of a complex adaptive system, particularly in the context of supply chain resilience. Table 1 has been adapted in-order to illustrate how Tukamuhabwa et al. (2015) captured these features.

Supply chain network resilience theory, which emerged from complex adaptive system theory, is posited to explain supply chain resilience. Whilst not all supply chains are complex (for instance, quarrying stone), by thinking of those that are (such as military or humanitarian missions) as a complex adaptive system, managers and researchers can understand these supply networks more completely and develop interventions that are more likely to be effective (Choi et al., 2001; Holweg & Pil, 2008; Li et al., 2010). Tukamuhabwa et al. (2015) stated that the features of a supply chain network resilience make resilience inherent within the network, since it is a system designed to adapt to environmental threats without violating its integrity as a functioning system. Adaptation, however, can only occur within the limits of the network's capabilities. If no adaptation is possible, it could result in a system's loss of integrity, malfunction or total destruction of the network's ability to function (Holland, 1992). This is a common characteristic of any system faced with a problem outside of its design specifications. The supply chain network resilience approach is a potential resolution, not a failsafe one, which Tukamuhabwa et al. (2015) failed to note. The schemas presented in our model determine the supply chain network resilience's responses and subsequent changes during the adaptation process; thus, adaptation and change occur through continuing co-evolution. This, in turn, increases the supply chain's ruggedness. Flexibility, i.e., adaptation, is key to achieving resilience, as it enables firms to respond to market dynamism and manage risks by reconfiguring their resources (Slack et al., 2009). Flexibility-oriented firms are more able to sense disruptions early, enabling themselves to react rapidly. They design their course of action quickly and reconfigure their properties in response to the recognized threats to gain competitive advantage. Flexibility is thus perceived as a proactive attribute of resilience.

For supply chain network resilience theory to be of use in the real world, the network model's properties must mirror real-world supply chains (Hearnshaw & Wilson, 2013). Military supply chains provide an excellent scenario for a real-world exploration of supply chain resilience improvement. These supply chains require agility and flexibility and a responsive system-to-system model that can enhance the robustness of an entire supply chain network with end-user considerations for decision-making both strategically and tactically. The data available about the United States Air Force's vision, tracking, and options supply chain problems, as reflected in information sources related to the Joint Expeditionary Force Experiment, a dataset established in 1999 by the United States Air Force (Cokus et al., 2000) and expanded every year until closed in 2013, were ideally suited for applying a supply chain network resilience approach. In real life, military supply chains/networks cannot rely

**Table 1** Comparison of complex adaptive system, SC and Supply chain resilience features (synthesized from Tukamuhabwa et al., 2015)

Complex adaptive system features	Description	Relevance to supply chain	Relevance to supply chain resilience
Adaptation and coevolution	Complex adaptive system agents change so as to cope with changes in other agents and its environment through self-organization. Complex adaptive system can also influence changes in other agents as well as in its environment	Due to environmental dynamism, the supply chain changes in order to adapt. Activities of individual firms may also influence the supply chain environment	Supply chain resilience is an adaptive phenomenon. Firms adapt to supply chain threats, but this may cause more changes in the environment
Multiscale/heterogeneous agents	Agents refer to entities that form a complex adaptive system. They operate at different levels in the system. Agents may be individuals, teams, divisions, or the entire organization. They are heterogeneous, given that they follow different schemas but aim to enhance their fitness within the entire system	Agents in a supply chain may be the individual firms. These operate at different levels with different rules, functions and objectives, e.g., supplier, manufacturer, distributor, retailer and customer	The resilience of a supply chain is a collective outcome from the interactions of different firms along the supply chain as they apply schemas (strategies and rules) to increase fitness/ survival
Schema	Schema refers to the norms, values, beliefs and assumptions shared by a group of individuals. It is a set of goal-led rules guiding the decisions and operations of individual complex adaptive system agents	Organizations within the supply chain have rules, visions, objectives, goals and strategies that guide their decisions and operations	Schemas include strategies and plans such as firms' Supply chain resilience strategies, which enable firms to modify their operations and adapt to their supply chain threats

on 'steady-state' conditions and are challenged by chaotic external pressures and turbulent change in vulnerable areas where there are high levels of operational risk (Pettit et al., 2013). Additionally, in common with all other supply chain research, creating dynamic capabilities that promote flexibility and the achievement of resilience at the lowest possible economic cost are of utmost importance in both the military and business environments alike (Davids et al., 2013; Fiksel et al., 2015).

Yoho et al. (2013) posited that defense and business supply chains have become similar because supply chain turbulence has generally increased, as has the imperative to have an efficient and effective flow of goods, services and information. Whilst the trade-off between

**Table 1** (continued)

Complex adaptive system features	Description	Relevance to supply chain	Relevance to supply chain resilience
Environment, dynamism and rugged landscape	The environment in which the complex adaptive system operates consists of other complex adaptive systems and is more complex than the complex adaptive system itself. It is rugged and dynamic, causing changes that the complex adaptive system agents must adapt to in order to achieve fitness. This adaptation may also cause changes in the World Health Organizational system as well as in the environment	In a supply chain environment, changes exist, e.g., in the supply base, statutory regulations, etc	Environmental dynamism creates threats. Supply chain resilience involves adaptation to both internal and external threats
Ability to learn	Agents in a complex adaptive system learn by obtaining information from their relationships within the system and the surrounding environment. It is through their dynamic learning that they are able to make decisions on modifying their capabilities and changing their schema in order to improve their fitness and performance	Organizational learning exists among firms/agents in the supply chain	Organizational learning enhances Supply chain resilience. Learning helps in adaptation by facilitating the modification of resilience strategies
Nonlinearity	There is a nonlinear relationship between the cause and effect of complex adaptive system events – a seemingly small event may cause large effects in the system (either positive or negative). Similarly, severe events may yield very trivial effects and, at times, no effect at all	A small change in the downstream part of the supply chain can cause amplified and oscillating changes in the supply chain upstream, e.g., the Bullwhip effect	Due to nonlinearity coupled with interdependence, seemingly small disturbances can result in massive supply chain threats. Survival depends on embracing Supply chain resilience strategies, such as increasing visibility and flexibility through multiple-sourcing

**Table 1** (continued)

Complex adaptive system features	Description	Relevance to supply chain	Relevance to supply chain resilience
Network connectivity/interaction	Complex adaptive system is composed of agents and their connections. The connectivity of these agents determines the complexity and the dimensionality of the complex adaptive system	Agents in a supply network have a physical connection that facilitates the flow of information, resources and materials. Such connections include telephone lines and the internet	Supply network connectivity and clustering facilitated by information flows facilitate collaboration, reduce opportunistic behavior, and enhance resilience
Dimensionality	Dimensionality refers to the degree of freedom an individual agent possesses in order to act somewhat autonomously	Supply chain entities have different objectives and constraints. They operate autonomously although their connectivity with other supply chain members causes some interdependence	Individual firms have partial freedom to make decisions. This contributes to self-organization, emergence and adaptation – crucial for Supply chain resilience
Self-organization and emergence	Decisions made by individual agents cause new structures, patterns, and properties to emerge at the system level without being externally controlled or imposed by any single agent. Some agents may have greater influence on the system than others, but they cannot control it entirely	No single firm deliberately controls or organizes the entire supply chain. The control or organization simply emerges in part because a firm cannot manage the entire extended supply chain. Each firm tries to achieve its goals but this in turn contributes to the collective behavior of the entire network	Resilience is an emergent feature of a supply chain. It is a result of self-organized processes that enhance adaptation. No single firm controls the resilience of the entire supply chain

efficiency and effectiveness is a concern, it is readiness that is the core operational requirement of military systems (Wilhite et al., 2014). Readiness incorporates responsiveness, flexibility and agility—fundamental to supply chain resilience and to supply chain network resilience (Day, 2014; Ponomarov & Holcomb, 2009). Absence of readiness results in failure, where profit, in the military context, is usually counted in terms of loss of life, not reduced profitability or disgruntled shareholders (Kovács & Tatham, 2009; Wilhite et al., 2014). An added complexity for military supply chains is that they frequently operate, especially in relation to the “last mile [re]supply”, in damaged or poorly-developed infrastructure areas, with over-strained local authorities, widespread threats ranging from theft to attack, as well as harsh

**Table 1** (continued)

Complex adaptive system features	Description	Relevance to supply chain	Relevance to supply chain resilience
Scalability	The same causal dynamics in a complex adaptive system may apply across all of its levels	Agents/firms at different tiers in the supply chain may have similar concerns, e.g., improving quality, delivery speed and reducing cost	Inter-relatedness within a supply chain and the presence of common schemas shared by firms are vital for the adaptation and survival (resilience) of the entire supply chain

conditions – sand, salt, cold, heat and combat (Tatham et al., 2017; Wilhite et al., 2014). Military forces have increasingly been deployed for humanitarian assistance and disaster relief (Bealt et al., 2016; Heaslip & Barber, 2014, 2016; Lis, 2016). This leverages the military’s ‘readiness’ strength (serving as peacekeepers and offering disaster relief) but is hampered by the different working styles, roles and guiding principles the military and humanitarian organizations have (Heaslip, 2012; Heaslip & Barber, 2016). The great number of players involved in the network further increases complexity. These specific performance challenges make military supply chains particularly suitable for whole-chain analysis using a networked approach to coordination and decision-making.

Several studies have developed models to address supply chain resilience and to create varying robust supply chain network resilience. For instance, Sebbah et al. (2013) developed a mathematical optimization algorithm to improve efficiency and scalability with regard to the distribution of heterogeneous commodities to forward operating bases in a theatre of operations. Ghanmi (2011) created a discrete facility location model, using mixed integer nonlinear programming, to determine optimal hub locations for the Canadian Armed Forces, supplemented with an aircraft routing model for the movement of cargo between the hubs. Skipper et al. (2016) proposed the use of a multiple objective linear programming model, again for the optimization of hub locations. Whilst it can help determine trade-offs between key network entities, its linearity precludes it from handling the vagaries of disruptions in the supply chain. Tsadikovich et al. (2016) incorporated an intermediary controlling module when developing an integrated demand-responsive scheduling system within a military supply chain consisting of transportation and maintenance operations. Glas et al. (2013) carried out a conceptual study using illustrative complex adaptive system studies. Adopting the contingency approach, they sought to provide a decision-support tool for defense contracting. They called this the performance-based logistics portfolio. As with the mathematical models, this tool provides limited applicability, as well as being empirically unproven.

The above literature review highlights a number of gaps in current approaches to making supply chains consistently resilient. None of the models cited present a whole-system solution. Each corresponds to a specific aspect of a supply chain. We seek to fill in this lacuna and build a more robust and flexible model that advances modeling research on supply chain network resilience by embedding in resource-based theory and system theory. This approach enables the incorporation of time, information, systems, heterogeneity, relationships, change, adaptation and co-evolution into a whole-system network model. Moreover, it can serve both military and commercial supply chain resilience needs. In a succession of

post-operational mission reviews, the United States Air Force consistently identified the management of vision, tracking, and options as core barriers to supply chain network resilience (Lis, 2016; Tsadikovich et al., 2016). Our proposal is a response to the call for solutions to the United States Air Force supply chain problem.

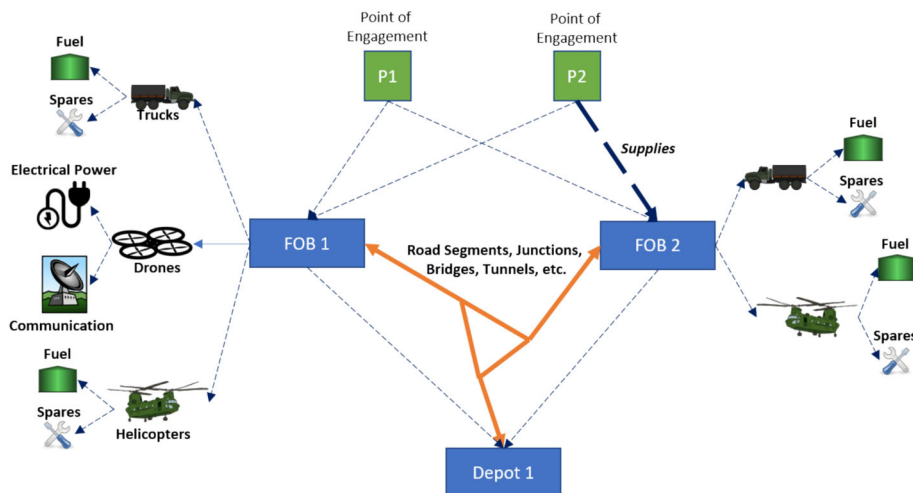
### 3 Methodology

With probability reasoning it was envisaged that our proposed model could replicate ecological biological systems and provide the ability to survive, adapt and grow in the face of turbulent environmental change. The approach develops a road map of people, process and technology requirements to support the military logistics process. More importantly, the model shifts easily into non-military contexts and can also offer civilian decision-makers the widest possible range of options available to maintain and adapt a cohesive supply chain. The probability reasoning method and other reasoning methods are main techniques employed in intelligent systems for processing uncertain and vague information (Guo et al., 2003). Probability reasoning provides the logic for inductive reasoning (North, 2010). The conceptual foundation is to view the assessment of probabilities as a process of going from our information to numbers that characterize uncertainty based on that information. This process depends on logical reasoning and must be consistent as the complexity of the judgments involved makes it impossible to build up probability assessments from information item by item. Therefore, if we are going to reason consistently about uncertain events using a numerical measure (as opposed, e.g., to qualitative descriptors). As a result, we implement the probability reasoning theory, as specified in its modern form by the Kolmogorov axioms (Wu et al., 2002). Our model is intended to: (1) Support decision-making and responsiveness to ensure the entire supply chain remains operational throughout the mission; (2) Permit propagation of decisions up and down the supply chain, rather than just in one direction; and (3) Generate a continuous flow of both supplies and information.

The vulnerability of supply chains, envisioned above as networks, can be conceived as the chances of one or more of its nodes (an actor/s in the supply chain) being rendered incapable of fulfilling its function in the supply chain due to forces acting directly on the node. For example, a supply truck might be vulnerable to destruction by enemy fire. Nodes rely on other nodes to carry out their tasks. Thus, a node can be incapacitated because it requires input from another node that is not functioning. In symbiotic relationships, reliance originates when one organization's output is the input for another supply chain member (Ivanov, 2020). A supply truck would have a dependency on its source of fuel, as it cannot transport supplies without fuel. Our model scores nodes based on the cumulative transitive dependency that other nodes have on it and identifies where they occur. The scores reflect how seriously the network would be affected by the respective node's incapacitation, including downstream effects. Our model thus identifies dependencies that are not obvious. For example, if the military operation is in a cold climate region, the supply truck and many other vehicles require antifreeze, making a reliable supply of antifreeze much more important than it appears at first glance. Having the model take this into consideration enables managers to anticipate supply chain problems and proactively deal with them before they occur rather than just reacting to failures. Managers can distinguish between nodes that may both have similar scores but differ in that some of them are more readily replaced.

The model is generalizable to any supply chain because all supply chain components can be treated as nodes in both military and commercial applications. The model can be





**Fig. 1** Basic node model of supply chain dependency flows

interpreted easily using a graphical interface because node dependencies are shown as dotted lines where the thickness of the line indicates the strength of the dependency (see Fig. 1). To address the basic requirement of identifying node dependencies, the first step was to provide visibility across the entire network. A simple, intuitive node-based representation of the supply chain network captures all its aspects, from strategic to operational levels. A straightforward example of this node-based representation is depicted in Fig. 1.

Nodes are described in terms of the type of resource they represent and the kinds of interactions they can have with other nodes of various types. There are three types of nodes: actor, physical or concept. Actor nodes are people, groups, or organizations (actors in a supply chain network resilience). Physical nodes are resources, objects or locations (environments in a supply chain network resilience). Concept nodes are ideas, goals, principles, policies, methods of organization, or operating procedures (which influence ‘adaptation’ and ‘learning’ (dimensionality in supply chain network resilience) (as noted in Table 1). Additionally, nodes can be described in terms of the interdependencies—for example, an actor could “defend” another actor node or “damage” a physical node. A list of potential dependency relationships between node types can be found in Table 2.

Algorithms developed by Dijkstra (1959) and Floyd (1962) were then applied to these networks of nodes and their relationships. This allows our model to capture the nonlinearity and network connectivity/interaction suggested by supply chain network resilience theory, and adding the vision, tracking, and options capabilities required by the United States Air force, as laid out in the Joint Expeditionary Force Experiment information sources. These algorithms look at the complete configuration and assign a dependency score to each node. They locate points of high dependency and evaluate their impact across the supply chain in the event of a disruption. This allows the classification of nodes in terms of capability, dependency, and vulnerability. Capability is the output of a node and can be either quantitative (fuel, transportation) or qualitative (supervision, subject knowledge). Its production is based on the provision of an output from one or more nodes, defining one or more dependencies, which it needs to realize its capabilities. Vulnerability is the direct susceptibility of a node to a phenomenon generated by an action or event. In the supply truck example described

**Table 2** Node and dependency relationships

	Actor	Physical	Concept
Actor	Actor supports Actor	Actor operates physical	Actor formulates concept
	Actor defends Actor	Actor maintains physical	Actor advocates concept
	Actor directs actor	Actor repairs physical	Actor opposes concept
	Actor supervises actor	Actor constructs physical	Actor accepts concept
	Actor opposes actor	Actor damages physical	Actor rejects concept
	Actor motivates actor	Actor destroys physical	Actor adopts concept
	Actor moves actor	Actor moves physical	Actor votes concept
		Actor accesses physical	Actor implements concept
Physical	Physical protects actor	Physical supplies physical	Physical supports concept
	Physical supports actor	Physical supports physical	Physical motivates concept
	Physical motivates actor	Physical constructs physical	Physical instantiates concept
	Physical damages actor	Physical destroys physical	
	Physical destroys actor	Physical damages physical	
Concept	Physical moves actor	Physical directs physical	
	Concept motivates actor	Concept supports physical	Concept motivates concept
	Concept directs actor	Concept motivates physical	Concept rebuts concept
	Concept supports actor	Concept instantiates physical	Concept contradicts concept
			Concept supports concept
			Concept subsumes concept

at the beginning of this section, the truck might represent a node capable of providing the transportation capability. It is vulnerable to damage or being destroyed by hostile actors and is dependent on its fuel depot's refueling capability. The fuel depot node too will have dependencies of its own. Accordingly, the truck node could be disabled by damage or disruption to itself, the fuel depot, or any of the nodes on which the depot depends.

Complex adaptive system theory specifies nonlinearity and network connectivity / interaction (Yarosen et al., 2021). To ensure these components exist in our model, the algorithms used in it were designed to exploit the nodes' ability to meet the primary capability, dependency, and vulnerability requirements. The node attributes and the possible node dependency permutations in Table 2 were integrated into the basic flow of the algorithms.

### 3.1 Data collection and model development

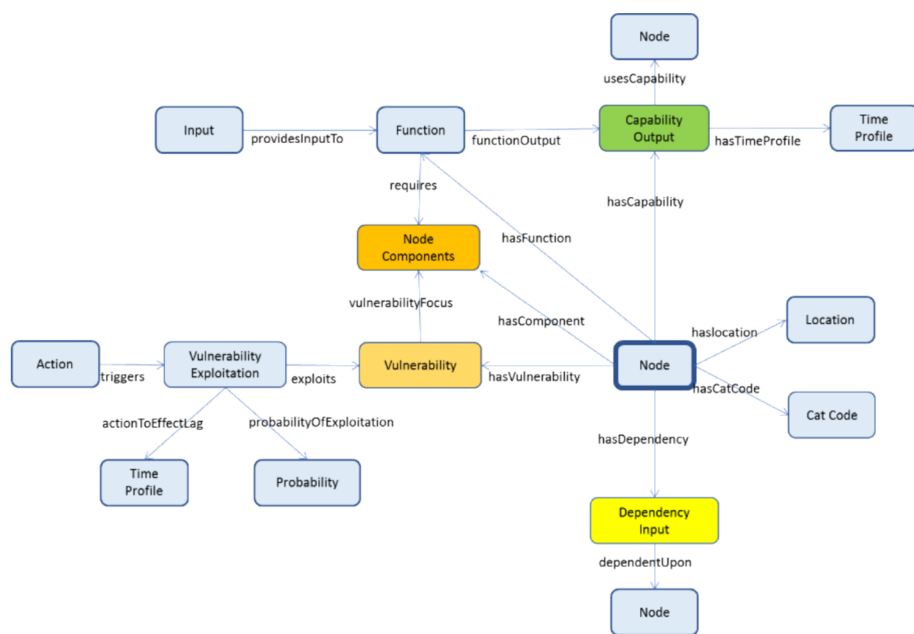
Joint Expeditionary Force Experiment is a large-scale Air Force experiment designed to assist the U.S. Air Force in preparing for the challenges of the 21st Century Expeditionary Air and Space Force operations. The Joint expeditionary force experiment link provides a virtual workspace to share information across its participants. Web tools were added to help manage operating and assessment tasks and to encourage collaboration, that we had access to. Observations were collected via a web-based tool during each experiment on ways to improve the design, planning, execution, and assessment of the Joint Expeditionary Force experiment. The Joint Expeditionary Force experiment link web portal was essential to access, share, and manage information across the experiment enterprise efficiently.

The United States Air Force's consistent identification of vision, tracking, and options logistics problems prompted the outlined approach and adoption of complex adaptive system theory, as detailed above. The combined attributes highlighted in Table 2 provided the rationale for the model. The model was designed to implement all the complex adaptive

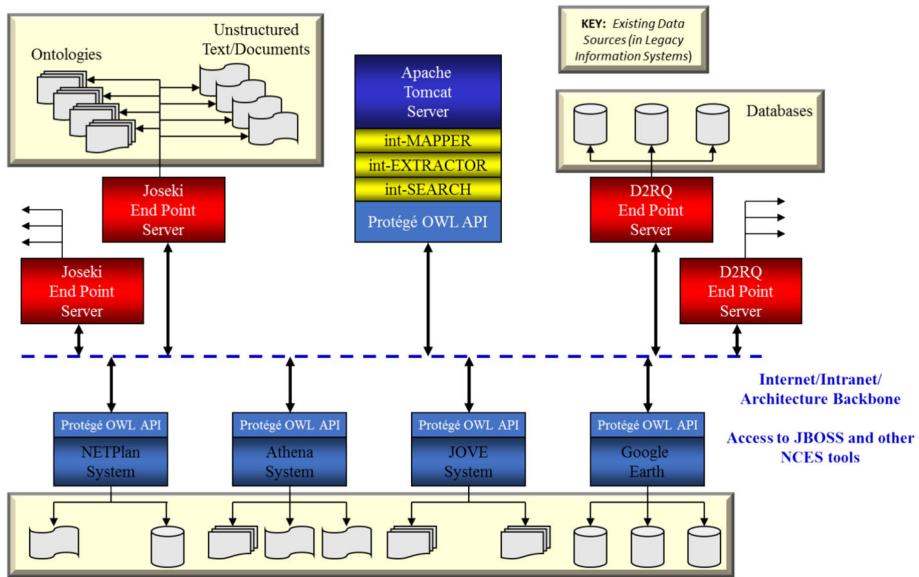
system features (Table 1) to existing data sources so that vision, tracking, and options was possible (Fig. 2). In addition to the capability, dependency, and vulnerability attributes, the node model contains additional information necessary to correctly model aspects of node behavior. Figure 2 shows the complete node model with the additional information incorporating temporal and other metadata. The United States Air Force's consistent identification of vision, tracking, and options logistics problems prompted the outlined approach and adoption of complex adaptive system theory, as detailed above. The combined attributes highlighted in Fig. 1, and Table 2 provided the rationale for the model. The model was designed to implement all the complex adaptive system features (Table 1) to existing data sources so that vision, tracking, and options was possible (Fig. 2). In addition to the vision, tracking, and options attributes, the node model contains additional information necessary to correctly model aspects of node behavior. Figure 2 shows the complete node model with the additional information incorporating temporal and other metadata.

The model was designed to implement the features of a complex adaptive system (Table 1) using data taken from the Joint Expeditionary Force experiment information sources. In addition to the capability, dependency, and vulnerability attributes, our model contains additional information necessary to correctly model aspects of node behavior. Figure 1 shows the complete node model for an example node with additional information regarding temporal and other metadata (a data set that describes and gives information about other data). Once tested and validated, the model was applied to live operational systems based on the Joint Expeditionary Force experiment data base. The architectural overview (Fig. 3) shows how the existing legacy systems were mined for data. This became a continuous process, permitting real-time updating and decision-making once field operations were live.

In this way, future models can be developed for economic, infrastructure, social, and information networks. These models will differ in terms of the number and nature of their



**Fig. 2** Outline of the node model



**Fig. 3** Information access architecture overview

nodes, the description of the actors and how they interact (e.g., support, defends, directs, and/or supervises) with other actors, the structure of communications networks, the physical equipment involved and the specific action options available to actors. Nevertheless, the model presented here is applicable to all the supply chain categories identified above. Each model identifies the interdependencies between nodes within the same network. More importantly, they allow for the specification of the interdependencies that occur between different networks. The resultant network model comprises multiple networks including producers, inter- and intra-theatre air and sealift capabilities, ground movement and last mile deliveries. Last mile resupply in a military context is the ability of a supply chain to provide logistics support to combat forces that are within 300 m–30 km of a point of engagement with enemy forces. The model provides updated situational awareness regarding each supply chain on a near real-time basis.

### 3.2 Data analysis

The algorithms can be applied in six distinct ways to the populated node model. These are captured in Table 3, which describes each application, the purpose it serves and the sort of information the analysis provides.

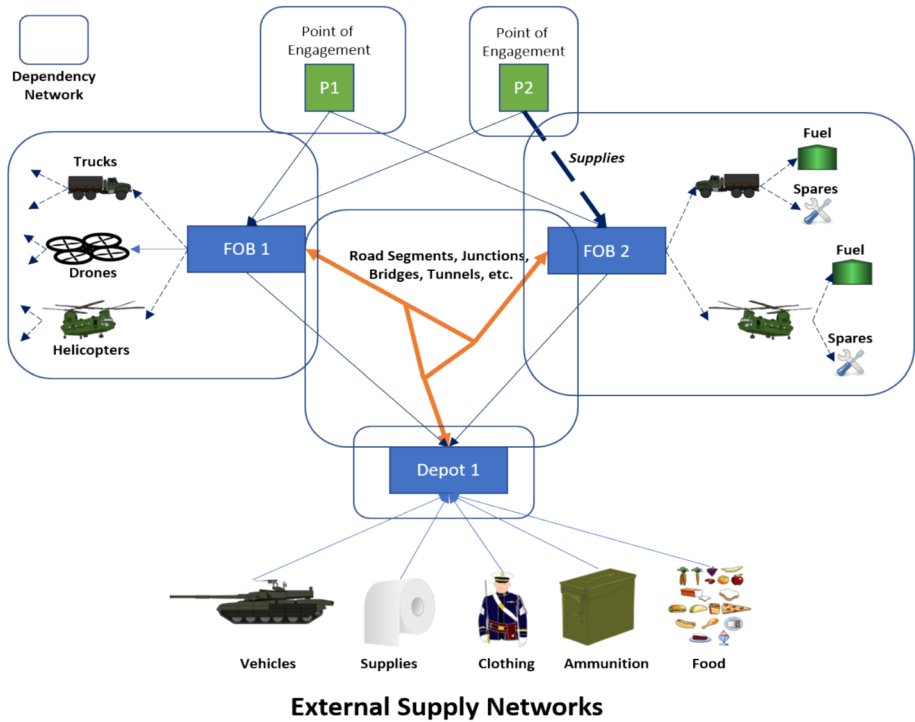
Considering networks and their differing dependencies in terms of their links allows the viewer to grasp the strength of the dependency (ranging from minor to critical), its nature (“supplies”, “operates”, “supervises”) and consequence vis-à-vis the output of the dependent node (and nodes that depend directly or indirectly on the dependent node) if it disappears. These dependencies create a cumulative dependency score for every node in the network. It enables all nodes to be ranked by how much disruption to the rest of the network their loss would cause. For instance, the chain of dependent nodes from depot 1 to forward operating base 1 (Fig. 4) contains one or more common route segments (roads, junctions, bridges) with

**Table 3** Reasoning capability categories

Algorithm	Purpose	Output
<i>Dependency-two options</i>		
Dependee	Identify how easily a node is impacted by changes to the capabilities of the node(s) upon which it is dependent	Nodes scored and ranked based on the cumulative dependency a node has on others (the need of a depot for fuel, electrical power, people, etc.)
Dependent	Identify the importance of a node to the overall functioning of the network	Nodes scored and ranked based on the cumulative transitive dependency that other nodes have on it (several supply depots all dependent on the same bridge)
Consequence	Identify the immediate consequence of a change in a node's capability and propagate this to all transitively dependent nodes	Identification and ranking of all impacted nodes in terms of the percentage change to the dependent capability
Probability	Identify and rank potential weaknesses in a selected transitive dependency chain	Calculation of a maximum probability that a dependency exists between a pair of nodes based on the combined probability of the correct identification of the nodes and links in the chain
Cluster	Discover self-contained sub-networks within the overall model that contain nodes whose transitive dependencies are above a user-provided threshold	Identification and ranking of (by number of nodes) sub-networks that contain nodes from multiple disparate networks
Completeness	Identify missing capability, dependency, and vulnerability attributes and, where possible, identify potential values and mappings	Identification and ranking of nodes based on combining their dependency score and the number of missing capability, dependency, and vulnerability
Instantiation	Identify the specific values for a node from a potential set of candidates	Identification and ranking of based on the number of other value instantiations that are either reduced or forced to have a specific value

the chain from depot 1 to forward operating base 2. This would result in higher dependency scores for the common nodes than ones that are not common. Each forward operating base is dependent upon its own network of trucks, helicopters and fuel and maintenance facilities.

Each node dependency (Fig. 4) is shown as a dotted line and the thickness of the line indicates the strength of the dependency. For example, P2 has a far higher dependency on forward operating base 2 for its logistics than it has on forward operating base 1 as shown by the thicker broken line. The strength of a dependency is rated from 1 to 10 and the relationship is identified based on the pair of nodes involved (as noted in Table 2). A value between 1 and 100 reflects the percentage change in the node's capacity if the dependency is not addressed (as seen in Fig. 4). For example, a truck could be equally dependent on a driver and fuel, giving them both a 5.0 dependency value. The lack of either a driver or fuel, however, means that the truck is non-operational (i.e., lacks the transport capability) regardless of how well the other dependency is met. In this complex adaptive system, using logic gate principles, the resulting value on each link would be 100, reflecting a 100% loss of the transport capability

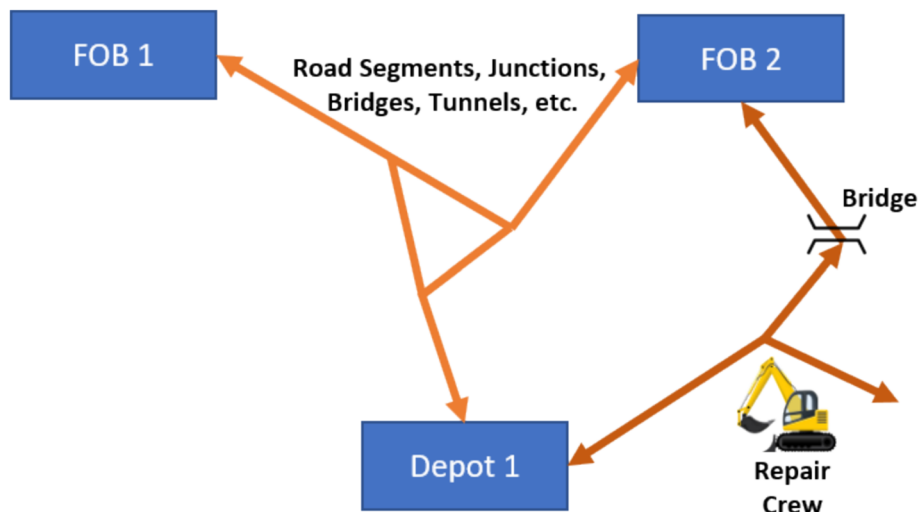


**Fig. 4** Network supply chain dependency model

if either dependency is not met. The value of a dependency that is helpful but not strictly necessary would be less than 100, reflecting that even without this input, the node could still operate at a reduced capacity.

The results of dependency and associated consequence analyses identify vulnerable points in the network that need to be resolved. Complex adaptive systems through the Casandra application was used to provide suggestions how the lack of resilience could be mitigated (Drabble & Schattenberg, 2016). For example, air assets are not directly dependent on the road network, but still may be indirectly and adversely affected by disruptions to it. Air assets are dependent on fuel supplies, which are dependent on the road network for transport to the forward operating base. By iteratively reconfiguring asset use, complex adaptive systems through the Cassandra application presents decision-makers with a ranked list of ways in which they could use the assets available to them to meet as many dependencies as possible, thereby increasing supply chain resilience by providing decision-makers with action options. This approach can be used to suggest modifications to the structure and capability of the supply chain nodes to increase their resilience, thus manifesting self-organization and emergent behavior (as itemized in Table 1). Figure 5 illustrates the situation where there is an alternative ground route from depot 1 to forward operating base 2 but at present, this cannot be used because enemy actions have damaged a road junction and a bridge along the route.

If these nodes could be repaired to restore their capability, then the existing but non-usable supply route would be reopened and the resilience of the supply chains between the depot and the forward operating bases improved. The network would allow forward operating base 1 to forward operating base 2 movement with additional movements to forward operating



**Fig. 5** Modified dependency model with suggested modifications

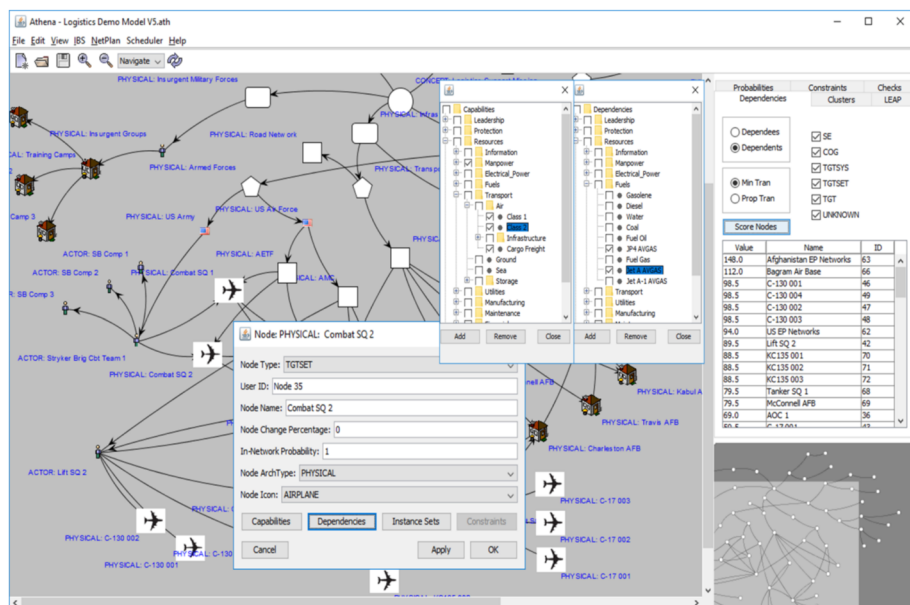
base 2 via the reopened route. Moreover, because the reopened route do not have any road segments in common with the current routes, this reduces the dependency on these transport infrastructure nodes significantly. This approach produces outcomes adapted to the prevailing environment, increasing resilience, flexibility, and thereby fitness. It does not require generic solutions to be developed in advance to deal with the range of possible changes in the supply network. It enables planners to examine the specifics of a situation and make the changes that would most effectively increase resilience. In other words, the optimal supply chain network resilience model will evolve organically as environmental changes evolve.

## 4 Findings

Ten different supply chain and logistics models were created. Five 8000–10,000 node models describing the delivery of a range of logistics from producers in the US, by inter-theatre airlift to Afghanistan via Germany and to the requesting forces via intra-theatre air and ground aspects were created. Five small scale 1200–1550 node models were also generated to capture intra-theatre and last mile resupply aspects of military supply chains. An example of a small-scale model (Fig. 6) demonstrates the occurrences and relationships between physical or concept nodes and their corresponding capability, dependency, and vulnerability values.

The dependency network is a complex adaptive system with the additional capability to alter the behavior of the network as potential issues are identified (Fig. 6). This capability is based on complex adaptive systems, planning and learning techniques, adopted from previous military applications. The dependency network can propagate changes easily from the tactical level to the strategic level within the same model, allowing planners to anticipate the full impact of these changes. Dependency analysis alerts planners to cumulative dependency increases of which they are usually unaware, especially in the complex adaptive system when other planners and systems are involved in decision-making with respect to the supply





**Fig. 6** Inter-theatre airlift dependency model

chain. This allows them to proactively make the kind of changes depicted in Fig. 5, controlling dependency and eliminating sources of failure.

Potential changes to ranking occur all along the supply chain—from the manufacturers of the materials who may be a continent away and have raw material issues, to the planes moving the logistics to the supply depot, or the trucks moving to the forward operating base 1—forward operating base 2 or forward operating base 1 or 2—depot 1, as depicted in Fig. 4. The values associated with dependency links, as determined by the model, can be used to assess the direct effects of an action or event on a node's vulnerability. Additionally, the model enables identification of the indirect, cumulative and complex adaptive system effects on the capabilities and dependencies of dependent nodes. It may be the complex adaptive system that in the network, a node, is highly depended upon but its loss can easily be compensated for by using other nodes with similar capabilities. The ability to distinguish between these types of nodes and the more important ones—both depended on strongly and having high consequence values (identifying a lack of resilience in the network)—allows decision-makers to focus on the most pressing resilience issues in the network.

## 5 Conclusions

The simulation model built with its easy to understand graphical user interface through the Cassandra application can help military commanders and civilian supply chain managers to ensure the maximum number of successful outcomes while minimizing attrition and collateral damage / loss. In this way, readiness is maintained because assets remain coordinated and executable at all times, adjusting for losses due to damage or re-tasking to higher-priority events.

As discussed, modern supply chains, epitomized by military supply chains in this instance, are highly complex, and out of necessity of highly choreographed network systems. Our dependency model allows decision-makers to immediately identify the direct and indirect effects of changes to the supply chain, whether planned by the decision-maker or caused by external events and actions. Through the complex adaptive systems and Cassandra application, the integrated planning and analysis capability of our model can provide decision-makers with situational awareness and visibility, enabling them to adapt and keep the supply chain operational throughout a mission. The ability to model networks from different levels of the supply chain (strategic, tactical and operational) within the same representation ensures that the effects of actions and events are propagated quickly across the supply chain and the command-and-control chain, supporting efficient tracking and option generation. These two combined capabilities may enable decision-makers to ensure a continuous flow of supplies to front line units. It further allows quick responses to mission changes and an increased tempo of operations. We believe that the ability to mine information from multiple data sources and fuse them into a cohesive model more easily provides a level of situational awareness not previously available in other models. While the analysis capability adds value, when asked, it is the ability to view the complete supply chain with all its direct and indirect dependencies that the decision-makers may find the most useful. Frequently, indirect dependencies are hidden that lead to a lack of resilience in the supply chain that thwarts even experienced planners. The approach we offer gives decision-makers a way to make these hidden dependencies more explicit.

In our view, the model will be able to reduce the generation times for usable supply chain models from days to hours. Nonetheless, it is the ability to reduce the projected manpower needed to maintain and update the supply chain model that may provide the greatest benefits to supply chain planners. For example, the logistics J4 planning cell for an air operations center usually has a staff of five personnel. The use of the data mining architecture may result in a reduction of the number of staff required for data management. This significantly increases the number of staff focusing on the actual function of the logistics cell. Thus, problems can be identified sooner, and more options developed and analyzed. Using this type of and analyzing a whole-system network supply chain, mission plans will have a greater probability of executing successfully, thus ensuring the continuous delivery of logistics materials.

Firms participate directly or indirectly in global supply chains and are embedded in the broader international trade system. They must abide by international trade rules and use the existing infrastructure. As a result, every practitioner, whether in the private or public sector, should be interested in the factors underpinning the resilience of the international supply chain system. Supply chain disruptions are becoming more frequent (Lopez and Ishizaka, 2019) and tend to lead to an excessive rise in costs, stock-out, delays, and inability to serve client demand, in addition to the firm's loss of market position. Under the Schumpeterian viewpoint (Vanpoucke et al., 2014), preserving competitive advantage through supply chain resilience in a shifting, unpredictable environment is challenging and requires supply chains to continuously reconfigure resources to fit fluctuating situations.

Modern supply chains, especially military supply chains, are highly complex, strongly choreographed network systems and their resilience must match their strength if they are to survive and thrive. Resilience requires two things—understanding what the problem is/could be and then being able to solve it or plan for it. It is argued that a resilient firm improves its competitive position and the responsive capability of its supply chain (Lopez and Ishizaka, 2019).

). The aim of the model outlined in this paper was to develop a dynamic, whole-system network model that uses the complex adaptive system Cassandra application to provide

timely, accurate, updatable and scalable information to military and civilian planners and decision-makers at all supply chain levels. Our model underscores the prevailing assumption that supply chain resilience will undergo important modifications following the COVID-19 pandemic (Blessley & Mudambi, 2022; Mena et al., 2022). Practitioners must recognize the developing trends to implement measures to stay competitive in future supply chain disruption scenarios. The required outcome in any supply chain disruption scenario—in turbulent, volatile and harsh conditions, whether because of conflict, peacekeeping or disaster relief—is maintaining a continuous supply. Our system, developed using supply chain network resilience principles, fulfills the requirement for continuous supply by providing vision, tracking, and options for decision-making, facilitating both understanding of the problem and timely, appropriate resolution.

Our model is a generic one and can easily be adapted to any situation in which there are interdependent networks across which the direct and indirect effects of actions and events need to be analyzed. Our model takes into account the complex adaptive system in supply chains where there are different networks of producers, transportation and storage groups, and consumers who need the materials to support their mission objectives and tasks. While the military context of these supply chains means they operate in a critical and volatile environment, all supply chains, even civilian ones, could profit from the capitalization of successful outcomes while curtailing marginal loss and secondary damage. A dependency network methodology aids in preserving competences in adverse environments of whatever sort by keeping resources synchronized and executable at all times and fine-tuning for losses or re-tasking for higher-priority events.

Evaluating networks in terms of their consequence value allows us to better understand their vulnerabilities. In addition to examining nodes in terms of how many other nodes depend on them directly or indirectly, this model also allows planners to examine how difficult it would be to route around a node if it was incapacitated and focus their efforts on nodes who's responsibilities cannot be assumed by other nodes in an emergency. Once implemented, the immediate benefit is a graphical user interface front-end, allowing the visualization of the tens of thousands of nodes and the thousands of relationships. Whilst here analysis was the primary goal, the graphical presentation provided by the modeling enables all decision-makers, irrespective of role or location, to have access to and see the same information. Visualizing an important node and its place in a given context alongside its dependencies and linkages with other nodes presents a useful holistic image of the bigger picture. A purely mathematical model with equations, tables and so on does not enable people to visualize the system as a functioning coherent network. Representing this information with icons is a more intuitive way of providing information. Because of the explicit links with the data-mining architecture, which is feeding the data directly into the model, the need for manual updating is eliminated. As such, the model provides the core features of supply chain network resilience and supply chain resiliency (adaptation, coevolution, learning, and emergence), all influenced by the landscape, its ruggedness and dimensionality (Table 1).

Learning from high impact disruptions must take into account contextual factors, as responses to new high impact disruptions may require a more creative and restructured approach (Sirmon et al., 2007). For low impact disruptions, major reconfiguration may not be necessary, but high impact disruptions require significant reconfiguration. For supply chains to become both resilient and innovative, their capacity to manage resources effectively and deal with risk is key. Our model enables decision-makers to affect nodes in a supply chain network in real time directly by dealing with their vulnerabilities and indirectly by circumventing their dependencies. This incorporation of dependency metadata about the strength and nature of connections differentiates our model from other approaches that only

consider indicators such as the number of outputs or inputs associated with a node or inter-connected sub-graphs (spanning node) when identifying the level of a node's dependency. Direct measures of connectivity such as these that fail to identify the highly dependent nodes importance is due to other nodes depending on the capabilities they deliver, not their location in the network, is crucial.

The COVID-19 crisis and a general rise in the severity and frequency of black swan events in recent decades have triggered calls for more substantial policy interventions to create the proper regulatory environment for increasing supply chain resilience. Our research and model can help policy makers in drafting better risk management decisions that reduce risk. At a strategic level, economic resilience policy will shape different industrial ecosystems to rebalance international supply chain networks, striving for superior supply chain resilience and enhanced economic and social resilience. The strategy can be achieved by better understanding of the interconnectedness of the supply chain network and by fostering and facilitating investment in the industry needed to promote resilience strength.

## 6 Limitations and future research

Our model was developed using a combination of techniques and approaches, based on complex adaptive systems with the Cassandra application, blending supply chain resilience, complex adaptive system and mathematics. Resource based view theory acknowledges that there are likely contingencies in the business environment that may affect the usefulness of different resources and capabilities for enhancing resilience (Iftikhar et al., 2021). Our model efficiently calculates and depicts the quantitative aspects. A main limitation at present is its ability to handle quantitative information only. For instance, it can provide options for how much travel to a given destination can be done with 10,000 L of fuel divided among 10 planes or 20 planes, and how those journeys differ. When it comes to handling non-quantifiable capabilities, such as supervision, knowledge or learning, the model in its current format falls short. To support qualitative as well as quantitative decision-making, further development is required.

A further limitation is that having been developed, and further enhanced, in combat situations, it has yet to be applied outside of the military environment. In view of the breadth of military involvement highlighted in our literature review, however, generalizability appears highly feasible, given the generic nature of the algorithms and the associated model. Kovács and Tatham (2009) showed that failure in any part of the military supply network is counted in terms of loss of life, not profits. This also applies to other sectors, e.g., humanitarian and disaster relief as noted in the literature review as well as to the domains of emergency services, healthcare and water, for instance. Further empirical work on post-conflict, multi-agency joint work would be useful to test the extent of the model's intuitiveness, its shared visual language and its ability to update itself continuously. The application of the model to multiple scenarios in a variety of sectors to continue testing its applicability and the level of resilience it provides should be encouraged. In our view, the study's limitations offer opportunities for future research.

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## Declarations

**Conflict of interest** None.

**Ethical approval** None (theoretical paper).

**Informed consent** None.

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