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Role of systems engineering attributes in enhancing supply chain resilience: Healthcare in context of COVID-19 pandemic

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ABSTRACT

In recent years, the area of supply chain resilience has received heightened attention as a plethora of new risks, ranging from climate change to cybersecurity and infectious diseases, have emerged as serious threats to operational performance. The COVID-19 pandemic, in particular, has exposed the fragility of global supply chains in many sectors. Given these concerns, supply chain networks, including those designed based on the principles of lean philosophies, are increasingly being re-examined as firms grapple with the challenge of strengthening the capacity to withstand, absorb, and rebound from unexpected shocks. Addressing the urgency of this imperative, this study presents a novel framework—based on theories and concepts in the systems engineering (SE) and supply chain resilience domains to enhance the resilience implementation capabilities that are lacking in many of today's firms. By applying a Grounded Theory methodology, this study develops and validates a conceptual model that identifies six core attributes fundamental to developing resilience capabilities in complex supply chains. The study concludes by providing examples of, and insights into, the role of these attributes in building supply chain resilience.

1. Introduction

Supply chain resilience (SCR) is a concept exemplified in practice by finding the best, most expedient solutions to problems as they arise within supply chains. The focus of SCR is recovery, or how quickly and efficiently the system can return to its normal state. The need to address escalating complexity has generated interest in SCR as disruptions within complex supply chains can cause critical failures. The term “supply chain” can be interpreted in many ways but is defined here in its broadest sense as “the network of organizations involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer” (Mangan and Lalwani 2016; Bhalaji et al., 2021).

Supply chain disruptions can arise from many sources. For example, the COVID-19 pandemic severely impacted the global supply chains of several essential products. In the healthcare sector, severe shortages of personal protective equipment, such as masks, face-shields, protective eyewear, gowns, and respirators, were reported (Bralio et al., 2021; Cohen and Rodgers, 2020). In the grocery sector, demand spiked sharply during several phases of the pandemic leading to disrupted food supply chains and out-of-stock shelves as panicked customers stockpiled key items, such as milk, rice, pasta, chicken, beans, medicines, laundry detergent, disinfectants, paper towels, and toilet paper (Hobbs, 2020; Knoll, 2020; Pisani and D’Innocenzo, 2020). Other less-essential items, such as auto parts, chips, and electronics were also interrupted for several months. According to a recent study, disruptions caused by the COVID-19 pandemic and geopolitical tensions cost the United States and European companies up to $4 trillion in 2020. The ability to foresee these factors and counteract the negative impacts is a supply chain's ability to be resilient.

What determines how disruptions affect a supply chain is the vulnerability of the supply chain network (SCN). Supply chain vulnerability, which was a relatively new and unexplored area of management research at the start of the 21st century, became a hot topic in the years directly leading up to the COVID-19 pandemic, at which point an explosion of research began (Peck, 2005; Golan et al., 2020). While the
terms “risk” and “vulnerable” are defined as “likely to be lost or damaged,” the term “resilience” is concisely defined as the “ability of a system to return to its original (or desired) state after being disturbed (Birkie, 2016; Ponomarov and Holcomb, 2009; Peck, 2005). A more recent and specific definition presented by Yao and Fabbe-Costes (2018, p.260) states that “Resilience is a complex, collective, adaptive capability of organizations in the supply network to maintain a dynamic equilibrium, react to, and recover from a disruptive event, and regain performance by absorbing negative impacts, responding to unexpected changes, and capitalizing on the knowledge of success or failure.” Along the same line, Rahman et al. (2021) stated that resilience refers to the ability of a system to be restored to its former state after a disruption. Lawrence et al. (2020, p. 3) echoed the same statement in defining resilience: “The term “resilience” is used to refer to the ability to return to a former state after being subjected to a period of stress.”

Now, the issue a SCN faces is not foreseeing disruptions, such as those previously mentioned, but maintaining a low threshold of vulnerability. This can be a tumultuous task as what ultimately makes a SCN vulnerable is the unpredictable frequency and intensity of catastrophes, disasters, and crises which impact individuals as well as firms and corporations (Zisdisin and Wagner, 2010). Notable disasters that have shown the true vulnerability of SCNs are the terrorist attacks on the World Trade Center on September 11, 2001, Hurricane Katrina of 2005, and Hurricane Harvey of 2017 (Atwater et al., 2014; Dowty and Wallace, 2010). These catastrophes disrupted central hubs and imposed a series of straining events on SCNs across the country, thus highlighting a serious problem: SCNs that reach acceptable performance levels tend toward operational stagnation, leaving little defense against the volatility of an uncertain global environment or recuperative properties in the wake of its turmoil.

Natural systems, in contrast, have an intrinsic ability and tendency to bounce back after an adverse event (e.g., a failure, an attack). This tendency is what Martin-Breen and Anderies (2011, p.7) refer to as resilience. A basic definition is “the ability to withstand, recover from, and reorganize in response to crises” (Martin-Breen and Anderies, 2011, p. 7). However, all resilience is not created the same. There is a need to consider the context in which resilience can be created, measured, and improved, especially in dealing with engineered systems (Katina and Gheorghe, 2014; Katina and Hester, 2013; Rahman et al., 2021). For this reason, the SCR literature covers the nature, subsequent problems, and potential solutions to SC disruption from various perspectives. Some of this work has been reviewed and will be identified in this paper. The unique contribution of this paper, however, is to present a framework for enhancing SCR through an evolved understanding of systems engineering attributes.

Employing systems engineers in the design and improvement of SC resilience may become more common as SCs continue to grow in scale and complexity. As many organizations do not yet have systems engineers on staff and systems engineering roles are being performed by a wide range of individuals from project managers to engineering managers, focus on the attributes of the systems engineering role is the most effective way to convey a clear framework for SCR creation (Arnold, 2000; Roe, 1995; Hossain et al., 2020). Proposing a framework grounded by theories and concepts in the systems engineering and supply chain resilience domains, and applying a Grounded Theory methodology, this study develops and validates a conceptual model that identifies six core attributes fundamental to developing resilience capabilities in complex supply chains.

The rest of the paper presents a framework and is organized as follows: A review of the resilience literature is presented in Section 2 followed by a more specific discussion of resilience as it relates to SCs in Section 3. Section 4 introduces a set of SCR factors that are merged with systems engineering attributes to form this paper’s theoretical SCR model. To enhance the resilience of the supply chain network, a theoretical model against the backdrop of SE principles is proposed in Section 5. Section 6 contains an explanation of grounded theory coding—the research method employed in synthesizing the systems engineering attributes—along with an elaboration of the systems engineering attributes themselves. The role of systems engineering attributes in enhancing SCR is detailed in section 7. In section 8, the framework is validated with a case study. Finally, the study implications are discussed, with conclusions drawn in sections 9 and 10.

2. Review of different perspectives of resilience

Bruneau et al. (2003) characterized four measurements for resilience in the notable resilience triangle model: (i) robustness (strength of the system), (ii) rapidity (speed at which a framework can re-visit its unique state, or if nothing else, a satisfactory degree of usefulness after an interruption), (iii) resourcefulness (degree of ability to apply data, mechanical, physical and human resources to react to a problematic occasion), and (iv) redundancy (degree to which a framework limits the probability and disturbance effects).

The research presented by Bruneau et al. (2003) also provides a deterministic static measurement of resilience loss (RL) of a network to a seismic tremor as indicated by Eq. (1). In this equation, the state of the corrupted framework at time \( t \) during the recuperation time frame is contrasted with the pre-seismic tremor quality (denoted as 100). The time at which the interruption happens is \( t_0 \), and the time at which the network re-visits its ordinary pre-disturbance state is \( t_F \). The state of the network framework at time \( t \), which is expressed as \( Q(t) \), is dependent on the execution measures used to restore performance.

\[
RL = \int_{t_0}^{t_1} [100 - Q(t)] dt
\]  

In Figure 1 the concept of system quality loss due to a disruption, followed by recovery is illustrated. This example, based on an earthquake, shows an instantaneous drop in quality as the system is presumably overwhelmed by the event. Following the disruptive event, the system is restored to its original quality over a period of time. RL is depicted as the concealed territory (resilience triangle). Bigger RL values show lower strength while more modest RL values suggest higher flexibility. Despite the fact that this methodology is used for an earthquake setting, the advantage is its overall appropriateness and applicability for explaining the impact of other systemic disruptions and recovery strategies – for example, supply chain disruptions. The proposed metric by Bruneau et al. (2003), which expects that the nature of the network framework is at 100% before the tremor, may be an unreasonable presumption. Moreover, a few issues with the versatility triangle are that (i) the region related to RL could be a troublesome measure for authorities to grasp, especially when given as a rate, (ii) the disruption has an accepted momentary effect, and (iii) the recuperation endeavors start immediately. In a supply chain disruption event, (ii) and (iii) in particular, may not hold.

The resilience triangle worldview has been applied in a few settings. For example, Zobel (2011), whose proposed metric is determined by figuring the level of the complete conceivable misfortune during a prolonged time span \( T^* \), is shown in Eq. (2). The boundaries include \( X \in [0,1] \) as the percentage of usefulness lost after a disruption, \( T \in [0, T^*] \) as
the time needed for full recuperation, and $T^*$ as a reasonably lengthy timespan over which lost usefulness is resolved. Zobel perceived that a similar degree of flexibility from the resilience triangle could be found from various combinations of $X$ and $T$, giving insight into the tradeoffs between lost usefulness and recuperation time for a similar degree of resilience.

$$R(X, T) = \frac{T - XT/2}{T} = 1 - \frac{XT}{2T}$$

From Figure 2, it can be seen that the absolute conceivable misfortune is determined as a three-sided zone $(XT/2)$ for a solitary troublesome occasion. This framework may be appropriate for representing recovery from some disruptions in the supply chain, such as an assembly plant that holds buffer stock in the event that it is needed.

Rose (2007) characterized economic resilience as the capacity of a substance or framework to maintain performance when an interruption occurs. This measurement quantifies both the proportion of the drop in framework yield that is avoided and the most extreme conceivable drop in framework yield, as shown in Figure 3. The proposed metric provided in Eq. (3) is a deterministic static model, where $\%DY$ is the difference between the non-disturbed and expected upset framework execution and $\%DY_{\text{max}}$ is the difference between the non-disturbed and most pessimistic scenario

$$R = \frac{\%DY_{\text{max}} - \%DY}{\%DY_{\text{max}}}$$

Rose (2007) likewise considered the time-dependent parts of recuperation in the meaning of dynamic resilience (DR). Dynamic resilience can be acquired by expediting repairs and recreating capital stock. The measure, $DR$, is an element of $\text{SORR}$, the output of the framework under hastened recuperation and $\text{SO}_{\text{rek}}$, the framework’s yield without hurried recuperation, where $t_i$ is the $i$th time step during recuperation and $N$ is the number of time steps considered. DR is portrayed graphically in Figure 4 and can be calculated using Eq. (4).

$$DR = \sum_{i=1}^{N} \text{SO}_{\text{rek}}(t_i) - \text{SO}_{\text{rek}}(t_i)$$

From a supply chain perspective, dynamic resilience might entail immediate, as well as longer term, strategies for recovery following a disruption. An example is product shortage resulting from increased demand. In such a situation, supply chain recovery efforts might include material substitution in the short term and an increase in production capacity in the longer term.

Henry and Ramirez-Marquez (2012) created a time-dependent resilience metric that quantifies resilience as a proportion of recuperation time to misfortune time. Given that the system performance at a point in time is estimated by the function $\varphi(t)$, three frameworks that are significant in measuring flexibility are presented in Figure 5: (i) the steady unique state, which expresses the ordinary performance of the system before an interruption begins at time $t_0$ and ends at time $t_0$, (ii) the disrupted state caused by a problematic event ($e'$) at time $t_e$ with effects felt until time $t_d$, which is depicted from time $t_d$ to $t_e$, and (iii) the stable recovered state, or new consistent execution level following the recuperation activity started at time $t_e$ which is depicted from $t_e$ onwards. Significant components of versatility that are shown in Figure 5 include the capacity to keep up regular activity preceding a disturbance, the capacity to fight off adverse effects after event $e'$, and the capacity to recuperate in an ideal way from $e'$. Eq. (5) notes that the resilient behavior adopted by Henry and Ramirez-Marquez (2012), is generally considered reliable.

$$\varphi(t') = \frac{\varphi(t_0)}{\varphi(t_e)} - \varphi(t_e)$$

As explained above, the numerator of this metric implies recuperation up to time $t_e$, while the denominator represents complete misfortune because of disturbance $e'$. This depiction by Henry and Ramirez-Marquez (2012) may well represent the typical disruptions in supply chains due to the gradual impact of the disruption and time required for recovery. An example is depletion of inventory following a disruption without immediate measures to replenish the inventory at the same rate.

Chen and Miller-Hooks (2012) introduced an indicator for estimating resilience in transportation organizations. The resilience factor, expressed in Eq. (6), measures the post-disturbance portion of demand that is expected to be met inside pre-decided recuperation spending plans. Parameter $\omega$ evaluates the greatest demand that can be met for the starting point objective in the origin-destination (O-D) pair $w$ following a disturbance, and $\delta$ is demand that can be met for the origin-destination (O-D) pair $w$ preceding the interruption. A constraint of this plan is the absence of commitment of pre- and post-disaster recuperation exercises representing recuperation time.
3. Supply chain resilience

Supply Chain Resilience is defined as the ability of a supply chain—as a system within any industry—to respond, withstand, and recover from an unexpected disruptive event to a more desirable state while avoiding failure modes (Blackhurst et al., 2011, p. 374; Cabral et al., 2012, p. 4831; Carvalho et al., 2012, p.331; Dong et al., 2016). Within the literature, the phrase “Supply Chain Resilience” is used synonymously with “adaptability” and “recovery” (Hosseini et al., 2019). The general consensus is a strong focus on the survivability of a supply chain. In their optimization model for resilience, Liu et al. (2014) discuss that in order to find the effectiveness of a supply chain and its ability to survive, one must first find the resilience “bottleneck.” This perspective was used to illustrate the existence of various levels of resilience effectiveness.

By focusing on the survivability of a supply chain through emergencies, industries are able to see what characteristics of a supply chain allow it to be resilient. It is important to focus on what can go wrong within a supply chain that could cause a need for a resilient supply chain. Liu et al. (2014) discuss proposed methods for a resilient supply chain and how feasible it is to achieve. The ability for a supply chain to be resilient, according to Cope and Liqing (2014), not only depends on the strategic planning of management, but the execution of individual contributors within that company. Most of the literature presented adheres to these basic ideas and principles. A few methods for creating a resilient supply chain have been found in the available papers. One paper proposed that SCR can be made through the study of three different perspectives: What can fail? How likely is that failure? What are the consequences of that failure? (Sheffi and Rice, 2005). Another focused on creating redundancies within the supply chain, primarily in the sourcing section of the supply chain. Other authors supported this perspective by recognizing that a supplier can be made more reliable or backup suppliers can be used to respond to supplier related emergencies (Torabi et al., 2015).

In this sense, resilience becomes a feature of the supply chain during the design phase. SCR has been described by authors as preparedness, adaptive capability, and proactive planning and design (Hohenstein et al., 2015; Kamalahmadi and Parast, 2016; Ponis and Koronis, 2012). Hohenstein et al. (2015) noted readiness as a novel concept at the time of publication, stating that it should be measured by the time elapsed during a SCs response and recovery efforts.

3.1. Readiness

The readiness phase of SCR, existing prior to supply chain disruption, is proactive in nature due to an understanding that disruptions will occur. In this sense, resilience becomes a feature of the supply chain during the design phase. SCR has been described by authors as preparedness, adaptive capability, and proactive planning and design (Hohenstein et al., 2015; Kamalahmadi and Parast, 2016; Ponis and Koronis, 2012). Hohenstein et al. (2015) noted readiness as a novel concept at the time of publication, stating that it should be measured by the time elapsed during a SCs response and recovery efforts.

3.2. Response

Datta et al. (2007) focused on the response phase of the resilience continuum during which the resilient supply chain adapts to...
perturbations in the environment and sustains acceptable performance levels. In the response phase, supply chain decision makers can employ design features from the readiness phase, such as turning to an alternate supplier in the event that a primary supplier has been disrupted. More generally, this phase consists of the deployment of previously developed logistics processes and competencies to maintain acceptable supply chain operational performance during and immediately following a disruption (Ponomarov and Holcomb, 2009; Wu et al., 2013). The notion of adaptability has also been suggested as a necessary component of response for the maintenance and control of the supply chain structure and function (Ponisis and Koronis, 2012; Kamalamahadi and Parast, 2016).

### 3.3. Recovery

Because many disruptions cannot be predicted and countermeasures may fail, the recovery phase of resilience will often be reached during disruptions. Several authors, including Cabral et al. (2012) and Carvalho et al. (2012) refer to the idea of recovery as “the system’s ability to return to its original state.” Additionally, effective recovery activities must be realized at a performance level that minimizes or eliminates adverse consequences for the customer. The effectiveness of recovery efforts is, therefore, a function of the available resources. The level of expenditure required to resume nominal operations may have a significant impact on

### Table 1. Resilience definitions in the extant literature.

| Authors’ Name                        | Definitions                                                                 |
|--------------------------------------|-----------------------------------------------------------------------------|
| Christopher and Peck (2004, p. 2)    | The ability of a system to return to its original state or move to a new, more desirable state after being disturbed |
| Peck (2005, p. 211)                  | The ability of a system to return to its original (or desired) state after being disturbed. The definition is rooted in ecology—the study of the relationships between living organisms and their environment—and was adopted because it resonates with the view of supply chains as interacting networks. |
| U.S. Department of Homeland Security Critical Infrastructure Task Force (2006) | An ability to recover from or adjust easily to misfortune or change. |
| Datta et al. (2007, p. 189)          | SCR is defined as not only the ability to maintain control over performance variability in the face of disturbance, but also a property of being adaptive and capable of sustained response to sudden and significant shifts in the environment in the form of uncertain demand. |
| Ponomarov and Holcomb (2009, p. 131) | The adaptive capability of the supply chain to prepare for unexpected events, respond to disruption, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function. |
| Williams et al. (2009, p. 253)       | The ability to react to unexpected disruption and restore normal supply network operations. |
| Haines (2009, p. 498)                | Resilience … is defined as the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover with an acceptable time and composite costs and risks. |
| Zsidisin and Wagner (2010, p. 3)     | SCR consists of the ability to return to normal performance levels following a supply chain disruption. |
| Klibi et al. (2010, p. 287 and 291)  | Resilience is the capability of a supply chain network to avoid disruptions or quickly recover from failures. The capacity of a system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents. |
| Yang and Yang (2010, p. 1903)       | In the literature, the term “resilience” is also borrowed from other disciplines to characterize an organization’s capability to recover to the original operating status before a disruption. |
| Kumar et al. (2010, p. 3721)        | Resilient supply chain networks need to be built having the ability to maintain, resume and restore operations after any disruption. |
| U.S. Department of Homeland Security Risk Steering Committee (2010, p. 26) | Ability of systems, infrastructures, government, business, communities, and individuals to resist, tolerate, absorb, recover from, prepare for, or adapt to an adverse occurrence that causes harm, destruction, or loss. |
| Blackhurst et al. (2011, p. 374)    | Companies, for example, can build resilience in their supply networks, which enhances the ability to absorb disruptions or enables the supply network to return to stable conditions faster and thus has a positive impact on firm performance. A firm’s ability to recover from disruptive events. |
| Verbano and Venturini (2011, p. 533) | The ability to recover following a loss is to minimize the consequences of risk situations. |
| Fregenzer (2011, p. 1)              | Resilience is a measure of a system’s ability to absorb continuous and unpredictable change and still maintain its vital functions. |
| Levesque (2012, p. 69)              | The ability to recover quickly from illness, change, or misfortune. |
| Machowiak (2012, p. 280f)           | Resilient supply chains can withstand the impact of major supply chain disruptions and catastrophes, without impacting the end customer and without incurring excessive recovery costs. |
| Carvalho et al. (2012, p. 331)      | SCR is concerned with the system’s ability to return to its original state or to a new, more desirable, one after experiencing a disturbance, and avoiding the occurrence of failure modes. |
| Ponisis and Koronis (2012, p. 925)  | The ability to proactively plan and design the supply chain network for anticipating unexpected disruptive (negative) events, respond adaptively to disruptions while maintaining control over structure and function, and transcending to a post-event robust state of operations, if possible, more favorable. |
| Cabral et al. (2012, p. 4831)       | Resilience refers to SC's ability to cope with unexpected disturbances. SCR is concerned with the system's ability to return to its original state or to a new more desirable state, after experiencing a disturbance, and avoiding the occurrence of failures modes. |
| Wieland and Wallenburg (2013, p. 301) | A supply chain can be resilient if its original stable situation is sustained or if a new stable situation is achieved. In this research, resilience is understood as the ability of a supply chain to cope with change. |
| Hearnshaw and Wilson (2013, p. 458) | For supply chain systems, resilience is critical as the success of firms is often determined by the ability of the system as a whole to continue to provide flows despite disturbances. |
| Hohenstein et al. (2015)            | The supply chain’s ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state. |
| Wieland and Wallenburg (2013, p. 655) | A supply chain can thus be resilient if its original stable situation is sustained or if a new stable situation is achieved as long as the supply chain is able to “bounce back from a disruption.” A supply chain is resilient if it uses resources that enable it to cope with change. |
| Wu et al. (2013, p. 676)            | Resilience is “the ability to respond and recover from a stockout disruption.” |
| Kamalamahadi and Parast (2016, p. 121) | The adaptive capability of a supply chain to the probability of facing sudden disturbances—to resist the spread of disturbances by maintaining control over structure and functions and recover and respond by immediate and effective reactive plans—to transcend the disturbance and restore the supply chain to a robust state of operations. |
| Lawrence et al. (2020, p.3)         | The term “resilience” is used to refer to the ability to return to a former state after being subjected to a period of stress. |
overall SCN resilience (Hosseini et al., 2016). Machowiak (2012) also focuses on the financial impact of recovery by stating that the internal cost of recovery must be manageable without passing the expense through to the customer. This ability of the system to bounce back from the localized performance minimum is noted as having an interdependent relationship with a SCN's readiness and response characteristics (Chowdhury and Quaddus, 2017).

3.4. Growth

At the far end of the resilience continuum is growth, meaning that the supply chain emerges from disruption with a competitive advantage (Kibli et al., 2010). This new post disruption operational state is described in the literature as being “more favorable” or “more desirable” (Cabral et al., 2012; Hohenstein et al., 2015). On one hand this may be realized by the Shehwart/Deming PDCA cycle (Deming, 1994, pp. 131–132) or the systems engineering system design method (Pet et al., 2013) that creates a feedback loop of system output used as system design input. On the other hand, environmental disruptions such as faltering demand will affect competing organizations, leaving the more resilient in a favorable position (Ponisz and Koronis, 2012).

Table 2. Supply chain resilience factors.

| SCR Factor   | Definition                                                                 | Reference                  |
|--------------|-----------------------------------------------------------------------------|----------------------------|
| Agility      | The capacity of supply chain firms to react rapidly, easily, and cost-effectively to unexpected changes in stock or interest. | Wieland and Wallenburg (2013) |
| Visibility   | The identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events. | Francis (2008) |
| Flexibility  | The capacity of firms to adjust to changing conditions with the least amount of exertion and time. | Millar (2015) |
| Collaboration| The ability of at least two independent firms to work successfully together, arranging and executing SC activities toward shared objectives. | Scholten and Schilder (2015) |
| Information sharing | The exchange of the right information between associates of a particular supply chain community for the lessening of supply chain risk. | Soni et al. (2017) |
| Redundancy   | The imperative usage of additional stock that can be utilized in the midst of a crisis. | Christopher and Peck (2004) |
| Adaptability | The ability of a SCN to change in accordance with new conditions and goals to allow endurance in the face of uncertainty. | Jain et al. (2017) |

4. Supply chain resilience factors

Several factors or components of SCR are identified in the literature. These factors and their relation to SCR are described in detail in the following section and are summarized in Table 2.

4.1. Agility

Christopher and Lee (2004) contended that agility is vital for creating strength in a supply chain. They expressed that SCNs with higher readiness are prepared to react rapidly to fierce conditions. Agility is characterized as the capacity of supply chain firms to react rapidly, easily, and cost-effectively to unexpected changes in stock or interest (Wieland and Wallenburg 2013). Agility is likewise characterized as a supply chain's capacity to react quickly to unforeseen changes in the market and convert those successes to business opportunities (Jain et al., 2008).

Supply chain agility ordinarily refers to a supply chain's capacity to rapidly adjust the organizational structure to the requirements of the customer and tasks when subjected to dynamic and violent perturbations (Dubey et al., 2018). Wieland and Wallenburg (2013) expressed resilience using two measurements: agility, which is the responsive strength of the system, and robustness, which is a proactive resilience technique. They concluded that agility should drive customer value in addition to increasing SC strength.

4.2. Visibility

Visibility, as characterized by Francis (2008) is, “the identity, location and status of entities transiting the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events.” Supply chain visibility has additionally been characterized as the ability to see upstream and downstream inventories, demand and supply conditions, and creation and buying plans in the end-to-end supply chain (Christopher and Peck, 2004). Saenz and Revilla (2014) examined the benefit of supply chain visibility in improving Cisco's flexibility in reaction to the Japanese tidal wave and quake of 2011. Despite the fact that the Japanese wave and seismic tremor brought about financial losses of $217 billion, Cisco endured practically no decrease in income. Within 12 h of the fiasco, Cisco was able to identify all of its suppliers in the affected area, from level 1 suppliers to providers of crude materials, and in less than 24 h was able to plan its customers requirements and field 118 requests (Saenz and Revilla, 2014). Chopra and Sodhi (2014) note that visibility in supply chain elements is vital to shield supply chains from interruptions.

4.3. Flexibility

Flexibility is characterized as the capacity of firms to adjust to changing conditions with the least amount of exertion and time. Millar (2015) contended that flexibility is an element of SCR that determines an association’s capacity to react to changes at the outset, quickly and with control of the supply chain environment. Rice and Caniato (2003) prescribed a hybrid flexibility approach to upgrade SCR. Adaptability includes adaptable transportation, adaptable sourcing, adaptable work orchestration and delay, all of which add to the strength of supply chains (Tang 2006a, 2006b; Christopher and Holweg, 2011; Pettit et al., 2013). Christopher and Holweg (2011) argued that flexibility makes SCs stronger by improving rapid adaptability during tumultuous conditions. In the literature, flexibility has been utilized with the expression ‘versatile ability’ (Soni et al., 2014). Pettit et al. (2013) discussed that supply chains with a lower level of flexibility in sourcing and order fulfillment are less hardened against disruptions.

4.4. Collaboration

Experimental and reasonable SCR literature has demonstrated that collaboration is a vital factor for building versatile SCs (Christopher and Peck, 2004; Juttner and Maklan, 2011; Pettit et al., 2013). Despite the fact that there is understanding among scientists that a coordinated effort can decidedly upgrade SCR, it is not clear precisely how cooperation impacts SCR. Joint effort in SC requires at least two independent firms to work successfully together, arranging and executing SC activities toward shared objectives (Scholten and Schilder, 2015). According to a report delivered by BCI in 2013, 58% of SC disturbances originate from first tier suppliers and these providers are of major concern to organizations. Blackhurst et al. (2011) indicated that joint effort among provider and purchaser can fundamentally lessen the probability of SC disturbances in the upstream SC and prevent negative effects of interruption from spreading throughout the entire SC.

4.5. Information sharing

Information sharing, or the exchange of the right information between associates of a particular supply chain community, is viewed as a vital driver of SCR by certain researchers (Soni et al., 2014, 2017; Datta
et al., 2007). Faisal (2010) posited that information sharing can strengthen the supply chain by reducing instability created by interruptions. They recommended that negotiation and supply chain material allocation before and after an interruption are important for supply chain resilience. Saghaﬁan and Oyen (2012) emphasized that data sharing coupled with an increase in inventories can result in supply chains that are more impervious and less vulnerable to disturbances.

4.6. Redundancy

Redundancy involves the usage of additional stock that can be utilized in the midst of a crisis, e.g., demand floods or supply deﬁciencies (Christopher and Peck, 2004). Additionally, redundancy involves the duplication of weak links with the ultimate objective of continuing tasks in the midst of a failure (Rice and Caniato, 2003). Redundancy, therefore, can be seen as a path to ﬂexibility (Ehrenhuber et al., 2015).

Redundancy tends to be a costly technique since it impacts the holding cost of inventory. Despite the fact that the organization utilizes alternate approaches to adapt to supply chain shortcomings and build strength, some time is required (Christopher and Holweg, 2011). This implies that repetition drives ﬂexibility, which empowers response through the adaptable organization of resources.

4.7. Adaptability

Adaptive capacities are described as enduring in the face of uncertainty by creating a system that changes in accordance with new conditions and goals (Jain et al., 2017). For example, if a store network has the ability to adjust effectively, it can return to its unique or improved state after disruption. Production network resilience centers around the system’s capacity to adjust to problematic events (Chowdhury and Quaddus, 2017).

5. Conceptual model

The interaction of SCR factors along the phases of the resilience continuum (Table 3) with each other and the systems engineering attributes creates the theoretical model for designing and improving SCs for increased resilience. The theoretical model is shown in Figure 6. In this model, the six resilience factors exist in and around the overlapping spheres of the four phases of the resilience continuum: readiness, response, recovery, and growth. The overlap creates an area of joint inﬂuence where the phases and their contingent SCR factors affect each other. This is an important feature of the model, e.g., an organization’s readiness for disruptive events enables faster more effective response; just as an effective response will be swift and allow resources to be devoted to readiness activities.

Because the phases of the resilience continuum progress in chronological order from readiness to growth, SC managers should assess resilience performance in the same order. Requirements engineering with a structured approach to elicitation, modelling, documentation, and maintaining of requirements is an appropriate methodology to employ towards this end. While these components of requirements engineering are primarily suited to function in the readiness phase, they may offer suitable alternatives when system performance data from actual disruption are not available for assessment.

Table 3. Relationships between SCR factors and the resilience continuum.

| Supply Chain Resilience Continuum | Readiness | Responsiveness | Recovery | Growth |
|----------------------------------|-----------|----------------|----------|--------|
| Supply Chain Resilience Factors  |           |                |          |        |
| Flexibility                      | X         | X              |          |        |
| Agility                          | X         | X              |          |        |
| Collaboration                    | X         | X              |          |        |
| Information Sharing              |           |                | X        |        |
| Visibility                       | X         |                |          |        |
| Redundancy                       |           |                |          |        |

Resilience in each phase along the continuum is enhanced by one or more SCR factors. Visibility and redundancy contribute uniquely to readiness by creating resilience in the system design phase and preparing supply chains for disruption response. These factors lose effectiveness once a disruption has occurred, and the response phase is reached. At this point in the continuum, the enhancing factors are information sharing, collaboration, and agility. Information sharing and collaboration, which enhance resilience in the response phase, must be initiated by development of protocols and relationships in the readiness phase. This is portrayed in the model by placement in the overlap of readiness and response phases. Information sharing and collaboration are examples of the joint influence between the two phases. The recovery phase, as the core of resilience, is enhanced by the three shared factors – collaboration, ﬂexibility, and agility. In the ﬁnal phase of growth, the model shows ﬂexibility as the sole enhancing SCR factor. The supply chain that is adaptable and aware of the changes required to survive disruption may use this trait to build a more robust system than competitors and move into the growth phase. The SCR resilience phases repeat in the tradition of continuous improvement.

The continuous improvement cycle is mirrored in the cyclical information flow from the SCR phase spheres through systems engineering attributes. This flow signiﬁes the continual evaluation, design, and improvement of SCR using SE methods. In this paper, these methods are deﬁned as six core attributes of modern systems engineering (SE): interdiscipliary, hierarchical view, requirements engineering, system design and integration, system life cycle assessment, and SE management. The SE attributes are discussed in depth in Section 6.2 but are discussed here as they contribute to the theoretical SCR model.

SC practitioners working to improve resilience in the readiness phase may beneﬁt from all six SE attributes. Requirements engineering is a vital starting point that will develop and strengthen the hierarchical view, which serves resilience priorities at all model levels in turn. This occurs as an understanding of the needs of all stakeholders is elicited, trade-offs are assessed, and preliminary designs are modeled and tested. System design then becomes vital to incorporating all resilience needs into a workable SC system. Life cycle management must also be considered in the readiness phase to incorporate risks in system design that are speciﬁc to products or processes served by the SCs over their life cycles.

The same system life cycle concerns can be employed to develop life cycle-appropriate strategies in the response phase; although, this is where SE management and interdisciplinary take center stage. SE management is shown in the model at the far end of both practice and utility due to the unpredictable nature of risk. Resources are well-used in the readiness phase to build shock absorption into the system, but extensive post-disruption management will determine much of the overall SC performance. In particular, managers with high performance in the hierarchical view attribute will be able to quickly make decisions based on system-level assessments of environmental changes.
The same SE management and hierarchical view attributes are necessary to manifest competitive levels of agility requisite in the recovery phase. By incorporating the interdisciplinary attribute, SCs may be able to break down functional walls and disrupt business-as-usual practices, becoming flexible and agile enough to rapidly resume desired operation.

As a culmination of events from the previous three phases, results of the growth phase are heavily influenced by all SE attributes. Requirements engineering may be singled out as data collected during the disruption that can be incorporated into the system model to generate updated requirements that flow back to the readiness phase.

The cyclical flows in the model are vital in generating maximum SCR located at the intersection of resilience phases and SCR factors. These include the flow from readiness to growth to readiness as well as the continuous flow of information from the system through SC managers imbued with the SE attributes.

6. Methodology

This paper applies a qualitative research approach to identify the systems engineering and supply chain attributes that impact supply chain resilience and to develop an applicable resilience framework in the context of the COVID-19 pandemic. Section 6.1 discusses the grounded theory methodology used to elicit the systems engineering attributes and summarizes key concepts in grounded theory coding. Section 6.2 discusses the systems engineering attributes derived from the literature that drive supply chain resilience.

6.1. Grounded theory coding

Grounded theory is a well-recognized qualitative research approach that was developed by sociologists Glaser and Strauss in 1967. The method initiates the collection of qualitative data without having a concrete hypothesis/concept in mind, unlike the conventional research approach which launches a theoretical framework and uses a case study for validation. The data collected is coded to separate, classify, analyze, and synthesize the data. Grounded theory is particularly useful for analyzing unstructured data in the form of text, observations, experimentation, videotapes, interviews, documents, and historical archives to study a phenomenon or concept that is non-existent, inadequate, or not well understood.

For this research, over one hundred sources were analyzed and coded. Data was derived from peer-surveyed meetings, peer-assessed diary articles, technical papers, and book chapters to compile, assemble, analyze, and record the data. NVivo 11 (QSR International) software was used to collate, analyze, and code the data. Figure 7 depicts the general steps in the process.

The process begins with data collection, followed by initial coding using codes from a data corpus. Initial coding is generally unchangeable, essentially linked to text or data mining, and helps to identify gaps in the analysis process (Charmaz and Belgrave, 2007). Further analysis synthesizes the initial codes into meaningful categories of related codes. The final step is derivation of an inductive theory based on continuous contrast between the different categories and their relationships. The coding process involves the following steps:

6.1.1. Phase 1: open coding

A series of codes directly related to the data is generated codes are assigned to separate elements to label a phenomenon (summarized in Table 4). Approaches to open coding include word-by-word coding, line-by-line coding, paragraph-by-paragraph coding, or whole document coding. Through deliberative involvement with the dataset for this research, we achieved theoretical sensitivity during the analysis, using the phrase-by-phrase and line-by-line approaches, along with the flip-flop technique, the red-flag technique, and the saturation specified in Corbin and Strauss (1990). It is crucial for the researcher to have no preconceived notions of what will arise from the dataset at the beginning of this process. However, the researchers kept the following question in mind during open coding: “What are the themes arising from the sources that help in the creation of another theory through the open coding process?”

6.1.2. Phase 2: axial coding

Axial coding follows open coding and is used to discover interconnections among classes and between classes and subcategories. The objective is to sort, examine, assimilate, and convert a large amount of information into fewer discerning classes (Creswell and Creswell, 2007).

Figure 6. Theoretical SCR and SE attribute model.
SE is a relatively new discipline with broad applications from health care to manufacturing to defense. It is, therefore, a well-discussed topic in the literature. A concise definition has been elusive and defining the role of systems engineers continues to be difficult. For these reasons and others, this paper is focused solely on the attributes of SE as drivers of SCR. In the following section, each literature-derived SE attribute is discussed in detail.

6.2.1. Interdisciplinary

Interdisciplinary refers to the coordination of different controls or functions to manage complex framework issues and provide excellent organization during the planning and advanced phases of a system life cycle. To successfully participate in complex framework issues in the frameworks design field, we need information and aptitude from unique areas, e.g., the technical, social, authoritative, and administrative. The interdisciplinary approach assesses the capacity of a framework's engineer in various areas, including integration, coordination and collaboration, hybrid thinking, common understanding of core problems, tolerance of ambiguity, application, adaptability, leadership, and communication and listening. This set of attributes gives a profound comprehension of the limit of an individual or group to address the range of basic measurements that are key to managing complex systems.

The interdisciplinary attribute is characterized by the system architect’s capacity to fuse various design controls into a framework, so that the constituent elements can work in concert with each other. This unique feature permits the designer to develop exceptional answers to address issues that might not have been clear in systems in which the interdisciplinary feature is absent, making it an important resource for any design group. All attributes are uniquely expressed in systems engineering terms. The interdisciplinary feature is characterized by multiple identifiers. The first is versatility, which is the capacity to alter arrangements and techniques as the prerequisites for the framework change. This identifies with the interdisciplinary feature as the systems engineer has the option to consistently coordinate different orders in their extemporized arrangement. To assume responsibility, the systems engineer must have the right authority. By having this characteristic, the systems engineer will be able to appropriately incorporate a large number of controls and facilitate their different inputs.

An indicator that may not be as evident is the capacity to endure uncertainty. When planning with a huge number of design groups, there will be countless questions. The frameworks engineer must be comfortable with this aspect of the workplace. A key trait of the frameworks engineer who depicts the interdisciplinary characteristic is the capacity to convey ideas and listen adequately. Without this skill, legitimate coordinated effort cannot be accomplished, and the result could be harmful. Another characteristic of the interdisciplinary feature is that of hybrid thinking, which is the capacity to iteratively create and execute innovative frameworks using human-focused encounters. Other aspects of the interdisciplinary feature that may not be a surprise are coordination and cooperation. With a feature that includes numerous design spaces and groups, the capacity to combine those groups and coordinate those areas is necessary.

A designer having a low-level competency in this trait would best be described as self-governing. What is implied by this is that the frameworks designer would prefer to work alone or in a small group that has a particular spotlight on one aspect of the framework. At the other extreme,
a frameworks engineer with high competency would be portrayed as community minded. This specialist would include numerous participants representing various aspects of the design to assemble a multifunctional team.

6.2.2. Hierarchical view

The hierarchical view represents the perception of an issue, its current circumstance, and its arrangement. Specifically, this is the perspective of a systems engineer – that is, whether the person is thinking about the whole system life cycle in general or just zeroing in on a set of disengaged parts. The degree of an engineer’s hierarchical view is characterized as a personal inclination to see complex issues from either a comprehensive or reductionist viewpoint. Besides the technical/technology parts of a system, it includes consideration of the entire range of human/social, authoritative/administrative, strategy, political, and data angles vital to a more complete perspective of a system. Similarly, new consciousness of economies, social orders, and environments as unpredictable versatile frameworks that cannot be completely caught through a solitary viewpoint increases the complexity.

The holistic characteristic can be defined as the capacity of a systems engineer to think in terms of both reductionism and holism. This attribute allows the engineer to see the system as a progression of parts, just as they have the option to zero in on one of the parts to fix an issue that may emerge. Being able to view both sides allows the systems engineer to focus on the planned cycle. This implies that issues at a lower ‘level’ of the plan should be recognized for their effect on the whole system. An engineer with this system characteristic would focus on the coordination of the various components and determine how they support each other. This feature should be clear whether or not the systems engineer is in a situation to make choices with respect to the whole system, a subsystem, or a single component. However, the reality is that reliance on power over planning and execution could affect a systems engineer’s capacity to use this holistic characteristic.

In conclusion, the systems engineer ought to have a general feeling of the hierarchical perspective of the system. This will allow the systems engineer to have the option of noting which parts of the proposed system are a mix of subsystems or a single component. This is significant for recognizing the parts of a system that guarantee that the system is appropriately considered, along with the effect of the system’s performance to the customer. A hierarchical view can likewise be passed on to singular groups or specialists to guarantee that everybody dealing with the system knows precisely how their work impacts different groups working on the task. An engineer who is inadequate in this area would be considered a reductionist. This systems engineer would focus on separating and examining each component as a solitary unit. By having a narrow focus, the engineer would focus on local optimization rather than global optimization of the system.

6.2.3. Requirements engineering/assessment

Requirements Engineering (RE) is viewed as one of the pillars of systems engineering. This characteristic is defined as the ability of the systems engineer to focus directly on the needs of the client and ensure that those needs are met. It is the ability to define and analyze stakeholders’ needs and communicate those requirements effectively to the project teams. RE involves eliciting, analyzing, modeling, documenting, and maintaining stakeholders’ requirements. The achievement of this task relies on the prerequisite of having an engineer or business executive who can retrieve, collate, and combine information from various sources, such as interview notes, scripts, and business archives.

Various performance indicators provide evidence of this RE characteristic. The first is whether or not the systems engineer has the ability to discern the groundwork and context of the system from the given requirements. The RE characteristic is important to ensure that the system falls within the design constraints and is built to the client’s specifications. Another key indicator is the systems engineer’s ability to trace the requirements throughout the system. To ensure the system meets the client’s expectations, every element as well as a combination of elements, must fit within the requirements of the system. An engineer with a strong RE characteristic should be able to see that these requirements hold true under any condition. Lastly, the performance indicator of flow-down activities must be considered. These activities include modeling, defining, and validating the requirements, with the engineering teams or the clients to ensure that all parties involved with the system have a clear and uniform understanding of the constraints of the system.

A systems engineer who is not proficient in this area would be focused more on internal forces, such as short-range fixes and plans, and tend to settle issues rather than taking on multiple perspectives. When an engineer has shown a high ability in this area, they tend to ensure that they take multiple perspectives as well as very specific requirements. Allowing for such openness creates a stronger sense of collaboration, keeping all interested parties invested in the overall outcome of the system. This engineer would also incorporate long term plans and keep their options open. This systems engineer would best showcase their abilities in a dynamic environment, with the opportunity to create order out of the chaos of constant change.

6.2.4. System design and integration

The fundamental purpose of SE is to coordinate and plan the sub-elements of the system to attain ideal systems execution by collecting and synchronizing the specialized inputs and checking the compatibility of the diverse interfaces to realize the best execution. The system plan, from a systemic point of view, emphasizes the organizational/managerial, policy/political, and human/social measurements of a complex
system. Furthermore, integration is centered on making the system perform as a ‘unity’, rather than as a sum of the parts. When an engineer possesses the ability to integrate, plan, and optimize a system, they have the capacity to observe the different components of the system and consolidate them to emphasize the importance of collaboration.

With the sub-element integration, plan, and optimization, there are performance indicators in the system's design, the primary purpose of which is to ensure the capacity to plan components that work in conjunction with each other in productive systems or subsystems, regardless of the scope or necessity of the systems. This feature is important in illustrating the innovativeness of the design because it permits for modern and one-of-a-kind strategies to combine subsystems and components. To ensure this, the capacity to perform unit testing is essential. To approve the components and prove that they work as expected to produce the required result. Checking the system as early as conceivably permits for alterations to be made before the plan or execution stages.

Another point is the concept of operation – usually, the capacity to see the framework from the point of an individual who will be utilizing the system, for example, the client or the client's workers. If the plan is not viewed from this point, it is possible that the system will be meaningless to administrators and to the client. The final point is approval and configuration. Approval and configuration are conducted towards the conclusion of the project to guarantee that the framework plan is attainable and meets the customer's requirements. This is conducted through all layers of the system as a strategy for checking each conceivable shortcoming of the system until the system is adapted to the customer's expectations.

An engineer without competence in this area would focus on the integration and optimization of components and subsystems at a local level. This approach may stem from seeing particular components and subsystems with ‘tunnel vision’. A profoundly competent systems engineer would focus on the global viewpoint of the system – that is, the integration of numerous subsystems, as well as the global result to guarantee agreement of the ultimate system.

6.2.5. System life cycle assessment

System life cycle consists of a number of consecutive stages that include concept improvement through generation, operation, and eventually, transfer of a project to a client. The determination and improvement of a system's life cycle depends on the encounter and execution of system design as iterative audits and choices. To be a competent system architect, a person must comprehend the information at each stage of the SDLC. A systems engineer with the lifecycle characteristic is one who considers the entire lifecycle of the system. This incorporates the planning stage through to staging of the system, and its long-term effects.

As with the other characteristics, the lifecycle characteristic possesses special features; primarily, that systems design must depict an understanding of the post-development configuration of the system. This configuration occurs once the system has been actualized and is being utilized by the client. It is critical to note that a customer receiving a system with a poor post-development result will be deprived of the required system output. The system's structure must reflect competency in applying concepts that indicate the use of advanced information to create and use the system. Having modern and novel concepts as well as utilizing proven and genuine ones will result in a rigorous framework that feels cohesive to the client. These concepts can be those that extend from individual component concepts or span the aggregate of the system, depending on the management of the client and the whole system.

An individual who is not well endowed with this quality would focus on the lifecycle stages and how precisely they are overseen. Conversely, a profoundly gifted systems engineer with this trait would focus on the total life cycle and apply iterative configuration strategies.

6.2.6. Management/Systems Engineering Management

Systems design administration is a specialized skillset with a broad understanding of trade standards to oversee and improve system execution. From the administrative point of view, a framework's design should create and maintain precise execution in different administrative aspects such as technical skill, understanding of team dynamics and relationship management, motivating, and developing others, self-development, communication, guiding people and managing conflict, problem-solving from a systems engineering perspective, creative thinking, and personal effectiveness. The previously mentioned abilities can be categorized into two segments: individual and group skillsets. The primary category (individual aptitudes) is important to the individual or personal capacities of a system's design and incorporates specialized aptitudes, self-development, problem-solving, imaginative thought, and individual viability. In addition to individual aptitudes, a systems engineer should have team-building skills and an understanding of group elements and relationship administration, as well as the ability to motivate others, communicate, direct individuals, and mediate conflict. In other words, administration of systems design ought to have a suitable level of individual and group aptitudes to be able to oversee complex systems issues.

The management aspect is characterized as having specialized abilities to supervise complex systems projects. This characteristic focuses on the capacity of a systems engineer to lead and organize a project by guaranteeing that both the objectives and prerequisites are met in an efficient and effective way.

Compared to the other characteristics, the management attribute possesses special characteristics. When undertaking a project, a key responsibility is managing uncertainty. Being able to weigh the pros and cons of different components and strategies and manage risk is vital. Another key capability is data administration. The system works as a huge combination of many complex components. In the event that the different components and their engineers do not have legitimate data, such as the due date, objective, or budget, it would be inconceivable that the project would be completed. Consequently, coordination of the data flow is key to successful completion. The system's designer must be capable of arranging and controlling the system. This should involve arranging the components in the order in which they are to be completed, as well as guaranteeing adherence to the proposed plan. Along these same lines are setup and choice management. Both of these indicators evaluate the planned configuration and guarantee that the proposed plan conforms to client specifications. Finally, the feature of quality design must be considered within the system's structure. The quality of the system refers to the adequacy of the different components as well as the system in its entirety. It is the duty of the manager to guarantee that the project is completed to the client's desired accuracy level.

An engineer with low managerial skills could be described as having low interpersonal skills, which effects the ability to properly convey business and technical ideas. A systems engineer with high managerial skills would use their exceptional interpersonal skills to easily convey business and technical ideas. Application of SE attributes are described in Table 8.

7. Role of systems attributes in achieving supply chain resilience

A systems engineer charged with the responsibility of ensuring the resilience of large-scale, complex supply chain systems must possess the necessary attributes to lead and manage this endeavor. The six attributes discussed in the previous section are all fundamental for designing and managing resilient supply chain systems. If one or more of the attributes is lacking, the system risks sub-par performance with respect to absorbing, responding to, or recovering from systemic shocks. The role of each attribute in enhancing supply chain system resilience is delineated below. These relationships are also shown in Table 9.

7.1. Interdisciplinary

The interdisciplinary attribute is a critical factor for achieving system resilience because
it consolidates diverse perspectives pertaining to the design, management, and control of the system. This characteristic refers to a systems engineer's ability to balance different inputs to meet desired performance outputs and to coordinate and share information among constituent subsystems to facilitate behavioral adjustments that meet customer needs. Ultimately, from a resilience perspective, the goal is to ensure that the design is adequate to absorb, adapt to, and recover from serious risk events.

Many examples exist depicting the importance of the interdisciplinary dimension in complex systems engineering. In a global supply chain, for instance, the interdisciplinary feature is required to ensure that conflicting goals are balanced. While financial considerations will always be an essential consideration in the design of a supply chain network, tradeoffs between financial targets and other factors, such as product quality, speed, volume flexibility, inventory levels, capacity demands, and political, economic, and regulatory risk in the external environment, will be necessary to deliver customer requirements. Each of these inputs is derived from a different source. Consequently, careful linking and balancing of priorities requires collaboration with all stakeholders to coordinate, synchronize, and align decisions and goals to achieve the desired end results.

The health care industry provides some insights into the importance of the interdisciplinary feature in designing, developing, and deploying systems that are both safe and cost-effective. Diverse sources of information shape a common understanding of the system's purpose and the specifications and tolerances necessary to achieve the desired performance results. Leading this effort requires exceptional communication and listening skills. When this aspect is lacking, a complex system may end up with a design that underperforms in adverse situations. In the context of the COVID-19 pandemic, this implies an understanding of the diverse inputs required to build health care supply chain resilience, such as material forecasting, inventory management, supplier relationship management, transportation management, and international logistics (Gooch and Gonzalez, 2021).

### 7.2. Hierarchical view

In systems engineering, a hierarchical view is essential for understanding the holism of a system, its boundaries, arrangement, and subsystem interfaces and interactions. A reductionist perspective that breaks down a system into constituent parts limits the visibility of the systems engineer. Conversely, a hierarchical view allows a systems engineer to develop mental models that identify potential points of failure where resilience needs to be strengthened.

Examples of the importance of the hierarchical view can be drawn from the automotive industry during the COVID-19 pandemic. Government lockdown mandates and other quarantine measures, which restricted the mobility of people, led to an unprecedented demand for electronic devices to facilitate work, online school, and home entertainment. As sales for these devices soared, the demand for semiconductor chips to support manufacturing and assembly of electronic devices correspondingly skyrocketed (Gooding, 2021; Preston, 2021). When lockdown restrictions lifted and automakers attempted to resume normal manufacturing operations, automotive manufacturers faced a serious shortage of semiconductor chips used in automobile infotainment systems, power steering mechanisms, brakes, and other parts. To compound the issue, the process of producing chips is complex and lengthy. Facing this issue, both General Motors and Ford Motor Company projected lost earnings for their organizations in excess of $1 billion (Wayland, 2021). Toyota, however, remained largely untouched by the chip shortage due to its stockpiling strategy developed to strengthen the company's resilience after experiencing raw material disruptions in the aftermath of the 2011 Fukushima disaster (Reuters, 2021). Toyota was able to develop this strategy because it recognized the interlinkages between its supply chain and other external systems in the broader environment and sought to strengthen points of fragility based on historical resource usage.

### 7.3. Requirements engineering

Requirements engineering (RE) is a core attribute of resilient systems because it ensures that all parts of the system have a thorough understanding of system requirements to support absorptive, adaptive, and restorative resilience capabilities. Moreover, it ensures effective collaboration among multiple functional areas to carefully and intricately

### Table 8. Summary of systems engineering attributes.

| Systems Engineering Attributes (6-SEA) | Application Process |
|--------------------------------------|---------------------|
| System Design and Integration         | Focus on new technology (Industry 4.0) for improved horizontal SC integration |
| System Lifecycle                      | Develop clear understanding of how resilience requirements will evolve over time. |
| Management                            | Lead and support diverse functions toward developing desired system resilience levels |
| Interdisciplinary                     | Possess knowledge that encompasses the abilities of all SC groups. |
| Hierarchical View                     | Focus on the overall concepts that enable optimal operation of the system as a whole. |
| Requirements Engineering              | Itemize failure modes that may affect the system once deployed. |

### Table 9. Systems engineering attributes that impact supply chain resilience.

| Supply Chain Resilience Continuum | Redundancy | Visibility | Information Sharing | Collaboration | Agility | Flexibility |
|----------------------------------|------------|------------|---------------------|---------------|---------|-------------|
| Interdisciplinary                | X          | X          | X                   |               |         |             |
| Hierarchical View                | X          |            |                     |               |         |             |
| Requirements Engineering/Assessment | X          | X          | X                   |               |         |             |
| System Design and Integration    | X          | X          | X                   | X             |         |             |
| System Life Cycle Assessment     |            |            |                     | X             |         |             |
| Systems Engineering Management   |            |            |                     | X             |         |             |
devise technical solutions that will minimize error corrections during the later stages of deployment and operation. The RE function communicates the system’s needs to all parts of the system simultaneously to ensure a universal and unambiguous understanding of system requirements to meet client needs. In so doing, the system can be designed at the outset to improve resilience to withstand, adapt to, and recover from disruptive shocks. Requirements engineering also involves documenting system requirements, verifying design completeness, analyzing, modifying, fine tuning, and validating requirements, and managing system needs. The ultimate goal of RE is to ensure that clients are satisfied, and costs involved in correcting errors later in the lifecycle are minimized by identifying, specifying, and implementing system capabilities at the design stage.

Requirements engineering can also incorporate aspects of specific design methodologies, such as design for safety, design for maintainability, design for usability, design for logistics, design for disposability, design for sustainability, and design for affordability. Such attributes of design would be implemented with the goal of strengthening the resilience of the system. For example, a system might employ design for sustainability features to strengthen all three aspects of resilience. Absorptive resilience strategies might include a backup renewable energy system to provide redundancy while adaptive strategies might focus on design to facilitate quick replacement of parts in the event of a breakdown. On the other hand, restorative design might consider modular components that minimize natural resource use.

Taking the example of design for usability in the context of the COVID-19 pandemic, food supply chain resilience can be strengthened by ensuring that manufacturing plants are capable of accommodating the packaging requirements of both restaurant and grocery customers. Thus, a shift in demand from restaurant to grocery items, due to stay-in-place orders, would not result in the dramatic shortages experienced at the retail level during the COVID-19 pandemic. Likewise, destruction of tons of agricultural products, such as milk, eggs, and vegetables (Yaffe-Bellany and Corkery, 2020), due to inconvertibility to the desired customer size and packaging specifications, could have been avoided.

**7.4. System design and integration**

With the advent of the Industry 4.0 era, system integration has become an imperative for supply chains. New advanced digital technologies have the power to transform supply chains from linear models, in which information is passed from suppliers to manufacturers to distributors to act decisively and completely in building resilience into complex systems. The energy industry provides an example of potential lifecycle issues in a complex system. As the agenda to replace fossil fuels with renewable energy strengthens, and improvements in engineering and technology lower the cost of investing in renewable energy, fundamental shifts in energy production systems are anticipated. The emergence of rooftop solar microgrids, for example, is expected to increase resilience to climate change but will require new production models that differ substantially from current production models for mass implementation (Masson et al., 2014). The gradual or partial phasing out of current production systems and replacement with new systems will have an impact on system resilience at every stage of the lifecycle. These energy changes have implications for pandemic situations to reduce the cost and improve the availability of energy to rural communities and to facilitate vaccine logistics, health care services, and Internet-based work and school requirements. The systems engineer, therefore, must continually lead the development of new resilience capabilities that adapt to and align with system needs.

**7.5. System life cycle**

All systems have a life cycle, which implies that changes over the duration of the system’s existence could have important resilience implications. In the case of a supply chain, as the dynamics of the system change, new solutions need to be developed to ensure that resilience measures remain commensurate with customer needs. These changes may not always be obvious, but could result from changing external conditions, new technologies, or shifts in stakeholder demands. To address the system life cycle aspect, both current and future resilient requirements must be planned from the conceptual design stage to final disposal, or alternatively, the system must be made sufficiently flexible to adapt to changing requirements.

The energy industry provides an example of potential lifecycle issues in a complex system. As the agenda to replace fossil fuels with renewable energy strengthens, and improvements in engineering and technology lower the cost of investing in renewable energy, fundamental shifts in energy production systems are anticipated. The emergence of rooftop solar microgrids, for example, is expected to increase resilience to climate change but will require new production models that differ substantially from current production models for mass implementation (Masson et al., 2014). The gradual or partial phasing out of current production systems and replacement with new systems will have an impact on system resilience at every stage of the lifecycle. These energy changes have implications for pandemic situations to reduce the cost and improve the availability of energy to rural communities and to facilitate vaccine logistics, health care services, and Internet-based work and school requirements. The systems engineer, therefore, must continually lead the development of new resilience capabilities that adapt to and align with system needs.

**7.6. Management/Systems Engineering Management**

Embedding resilience features into complex systems requires exceptional skills to lead diverse functions, coordinate information flows, moderate consensus decisions on competing priorities, and manage change. The systems engineer must be capable of providing the right support to iteratively design, model, test, and integrate system components to ensure the intended level of system resilience is achieved. Beyond the technical aspects mentioned, the systems engineer must also have the managerial skill to persuade decision makers and motivate actors to act decisively and completely in building resilience into complex systems.

**8. Validation via case study**

To validate the attributes that are fundamental to supply chain resilience, the case of NYU Langone Health, a New York City based medical center with over 400 employees in the supply chain area, can be used. Before the COVID-19 pandemic hit New York city, the organization had already recognized the likelihood of a severe disruption in the personal protective equipment (PPE) supply chain, as over 70% of US PPE was being sourced from China. The company itself also sourced over 99 percent of its PPE through a single distributor via a lean supply chain that operated on a just-in-time basis. This posed a precarious situation for the supply of critical PPE items, such as the 109 million pairs of gloves the organization purchased yearly. While the company had no roadmap in place to handle disruptions, it was able to quickly pivot to build resilience in its supply chain.

It is well-known that healthcare has typically lagged manufacturing in the supply chain area; however, NYU Langone was able to benefit from supply chains for vaccines and other medical supplies in pandemic situations. Applications proposed include real time data capture of cold chain temperatures, inventory levels, product location, and logistics services (Quiros and Alam, 2021).
the expertise of at least two senior members with external experience – a recently hired VP of Supply Chain Management and a Director of Freight Management. The attributes that propelled resilience in the PPE supply chain are discussed below (NYU Langone, 2020).

- **Interdisciplinary**: The organization’s supply chain function partnered with finance, clinical operations, infection prevention and control, and environmental health and safety to rapidly identify the most critical items that risked being short and to assess the quality requirements against the company’s specifications. Early recognition of a potential disruption led to early placement of orders before healthcare facilities were placed on allocation. The team also met to assess inventory levels and anticipated burn rates daily. This approach increased the organization’s agility, and according to the VP and CFO of the organization, allowed NYU Langone to remain “one step ahead” with decisions made “in hours and days, not weeks and months”.

- **Hierarchical view**: By taking a global view of the supply chain and focusing on the ultimate purpose of the PPE products, the organization was able to identify and circumvent potential disruptions in various areas of the supply chain. A prime example was the sourcing of helmet respirators to substitute for N95 masks. Along these same lines, suppliers were identified worldwide to hedge against the risk of disruption from clustering in a single country. Similarly, transportation options via chartered flights were negotiated with third party providers.

- **Requirements engineering**: NYU Langone ensured that the suppliers it identified were capable of meeting the required safety and quality specifications. Specifically, the organization implemented a rigorous screening process with 100% inspection to identify subpar and fraudulent products that could disrupt the supply chain.

- **System Design and Engineering**: NYU Langone implemented new policies and requirements to redesign its supply chain to increase resilience. As the Director of Logistics and Inventory stated, “People were truly thinking outside the box, trying to anticipate the next need so that we didn’t skip a beat.” Another example is the organization’s partnership with Real Estate Development Facilities to increase its warehouse storage space from 50,000 to 150,000 square feet and thereby accommodate 3–6 months of PPE supplies. The company described this design strategy as “supplementing just in time deliveries with just in case reserves”.

- **System lifecycle assessment**: Supply chain needs were not only reviewed for the present but also continues to be reviewed to meet resilience requirements of the organization in the post-pandemic period.

- **Management/Systems Engineering Management**: NYU Langone’s strategy to build a resilient supply chain was led by its executive team from the beginning rather than handed off to mid-tier or lower-level personnel. By elevating this responsibility to the highest levels, the organization demonstrated the role of management and leadership in motivating and persuading supply chain participants through its iterative design process of building a resilient supply chain. As the VP and CFO of NYU Langone indicated, “it came down to agility, execution, and muscle.”

9. Implications of the study

By reviewing the resilience and systems engineering literature, a new theoretical model for the creation and improvement of SCR has been presented in this paper. SCR is a relatively new research topic and the impact of specific systems engineering attributes on it have not been previously studied. It is the authors’ opinion that this approach is highly germane and can offer SC researchers and practitioners an enhanced level of clarity in the strengthening of SCs against disruption.

Current SCR literature primarily discusses the nature of resilience and specific remedies against disruption in the form of the SCR factors isolated in this paper. By applying systems engineering methods, tools, and understanding to the design and implementation of the SCR factors into SCs, the problem can be approached holistically and systematically. Though the attributes of systems engineering are widely understood to be critical to the effective design and management of complex modern systems, the roles of systems engineers and the precise definition of the discipline itself remain contentious. For this reason, the focus of this paper is on systems engineering attributes which can be effectively employed to achieve SCR by interested SC practitioners, rather than systems engineers only.

SC managers can use this information as the basis of a paradigm shift from reactionary, reductionist SC design and management approaches to modern systems engineering methods. This pairing of SCR factors and systems engineering attributes is inherently complimentary and can guide SC managers and practitioners towards answering the question of how to implement theoretical SCR concepts into physical SCNs.

10. Conclusion

The presence of threats to organizations via their SCs has been established by events in the chaotic modern world - the COVID-19 pandemic being one of the most notable disruptive events in recent times. Efforts to create more resilient SCs—those with the readiness to respond, recover, and grow from disruption—can be bolstered through the practice of systems engineering in their design and improvement. Because many organizations may lack systems engineering personnel, the attributes of systems engineering are discussed in this paper so a wider audience may benefit from the research.

The synthesis of resilience ideals into the phases mentioned above is a novel concept intended to clarify a broad range of concepts from the literature into a more concise format. The nature of this fusion is rooted in the integrative holistic thinking prescribed as the engine powering this paper’s theoretical model of SCR implementation. Grounded Theory Coding serves as the mechanism for gaining that holistic understanding of the SE literature presented as the six SE attributes.

SC managers dealing with real-world disruptive events may benefit from incorporating SE attributes in their work. As the result of the rigorous grounded theory coding methodology, these attributes represent a distillation of extensive research to enable more focused building of resilient supply chains. This proactive resilience-building approach is validated by the success of practitioners applying the SE attributes of requirements engineering and system design. This approach benefits from tracking resilience using the SCR factors as leading indicators, rather than the trailing indicators of traditional risk management.

Future research should address the limitations of this paper by including case studies to validate the theoretical SCR model. Though the SE attributes have been well established as drivers of positive results in the face of complexity, ambiguity, and uncertainty in both industry practice and academic research, their successful implementation into SCR model-driven resilience would mark a further milestone in the pursuit of deeper SCR understanding and higher SCR performance.

Declarations

**Author contribution statement**

Niamat Ullah Ilbonie Hossain: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Steven Fazio & Jeanne-Marie Lawrence: Analyzed and interpreted the data; Contributed materials, analysis tools and data; Wrote the paper.

Ernesto DR Santibáñez Gonzalez, Raed Jaradat & Maria Santos Alvarado: Contributed materials, analysis tools and data. Wrote the paper.
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