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Article

Sustainability in Supply Chains through Rapid Capacity Increases and Minimized Disruptions

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Abstract: We examine the impediments to rapid recovery from a supply chain disruption through rapid supply chain growth in capacity. We explore how to minimize the effects of disruptions in supply chains that could be caused by pandemics, wars, supplier down times, absenteeism, distributor bottlenecks, etc. The tools we use include reliability theory, logic, simulation, and other methodologies. Our objective is to better understand supply chain disruptions and to propose solutions to the sustainability problems currently being experienced within supply chains. The authors use models to better comprehend how to avoid supply chain structures that are easily disrupted. Included among the findings are that disruptions cause the loss of production capacity; thus, the ability to rapidly increase production capacity in the same or other parts of the supply chain becomes paramount. Furthermore, structural redundancy can help alleviate the loss of capacity coming from a disruption. One purpose of the models is to foster a basic appreciation for the different lead times and fixed costs associated with capacity expansion of the various supply chain components. There are implications for where within the supply chain additional robustness and capacity are needed.

Keywords: adaptive response projects; bottlenecks; reliability; supply chain capacity; supply chain disruption; supply chain resilience

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1. Introduction

Sustainability has different meanings to different scholars. For some, it means the transition from non-renewable, carbon-creating sources of energy to renewable, non-carbon-creating sources of energy. For others, it means the capacity to continue in the face of disruptions. The operations management textbooks, such as [1,2], inform us that there are three components to sustainability—economic sustainability, social sustainability, and environmental sustainability. Most large capital firms have changed their business models to include sustainability as one of their objectives. For purposes relative to this article, the focus is on economic sustainability—continuing to produce products and deliver services at a level that is consistent with the past. Currently, we are witnessing a plethora of supply chain disruptions. For the most part, these disruptions were caused by the COVID-19 pandemic and possibly could be caused by many other phenomena such as globalization, lean systems, employee absences, employee strikes, equipment breakdowns, and so on. For instance, one cause of the absence of supply chain resiliency (SCR) is the lack of redundancy in supply chain structures [3]. Many automobile manufacturers have found that at the extreme upside end of their supply chains, there are very few choices for suppliers. Takata Corporation, as one such example, supplied the airbags for dozens of automobile manufacturers and their older airbags began to fail after being installed in cars for several years. The result was the need for the replacement of some 25 million airbags in cars worldwide [4].

Supply chain disruptions have to do with the resiliency of the supply chain. SCR is a part of the more subsuming concept of supply chain sustainability. Supply chains that are easily and frequently disrupted are not sustainable. A myriad of definitions and frameworks have been proposed for SCR [5]. This paper elaborates upon those and utilizes them to develop real, practical solutions to supply chain disruptions. This article proposes pragmatic solutions to the problem of SCR. It uses reliability theory to identify where possible problems exist in the supply chain structure and it views a supply chain disruption (SCD) as a loss of capacity; therefore, it involves a project that restores in some way the lost capacity. Whatever is done in response to a disruption we will call an adaptive response project.

Our purpose in pursuing this research was to (1) suggest supply chain structures that were resilient to supply chain disruptions and (2) find and suggest faster ways to respond to and repair disruptions in supply chains when they do occur. We call these repair-or-replace initiatives adaptive response projects. We believe this is important because calamities will increase to five times the present rate in the next 50 years [6]. The International Federation of Red Cross and Red Crescent Societies (IFRC) collected data between 2008 and 2017 and reported that roughly 3751 natural disasters affected 2 billion people and caused more than USD 1.6 trillion in damages [7]. So, it becomes important that, when these calamities disrupt supply chains, the disruption can be repaired/replaced rapidly and at minimal cost. The methodologies we shall use in this study are mathematical reliability modeling, structural and visual modeling, logic, and the Theory of Constraints (TOC) understanding of supply chains. The outcomes of this study are (1) to build redundancy into supply chain structures and (2) to focus on components in the supply chain with the longest capacity expansion lead times. The contributions of the study are to (1) understand that fixes to SCD events are accomplished with adaptive response projects and (2) be able to conduct repair/replace adaptive response projects faster. Speed of response becomes the ultimate solution to supply chain disruptions.

The rest of the paper is organized as follows. First, an extensive literature review is presented in which major contributors are cited. Next, models and their analyses are developed. A discussion section then proposes the possible implications coming forth from the research. Finally, conclusions are drawn from the modeling analysis and the discussion.

2. Literature Review

This literature review investigates articles discussing SCR in general and focuses on four relevant topical areas: (1) definitions, frameworks, measures, and models (2) innovative SCR studies, (3) systematic literature review articles, and (4) the use of TOC [8] and critical chain project management (CCPM) concepts as they relate to SCR.

2.1. Definitions, Frameworks, Measures, and Models

Ribeiro and Barbosa-Povoa [5] reviewed definitions and quantitative models of SCR through recourse to the academic literature. They performed a content analysis of 39 articles. Additionally, definitions for SCR were examined and no consensus was found. They proposed their own definition that subsumed the four main elements of SCR, namely focus event, adaptive response, speed, and performance level. Their investigation led them to the conclusion that most quantitative models do not include all four elements of SCR. They suggested a need for an integrated holistic approach that addresses the basic supply chain characteristics and the SCR elements. Brusset and Teller [9] defined SCR as the operational capability for a disrupted supply chain to correct itself and be stronger than before. They surveyed 171 managers to test four hypotheses about SCR. From their conceptual model, they learned that tighter integration between echelons and increasing flexibility led to greater resilience. Wieland and Durach [10] created an updated definition of resilience when used in connection with supply chains. Their goal was to integrate two distinct definitions of resilience—one dealing with the ability of a supply chain system to bounce back from an impeding event and the other relating to the capacity to adapt and transform.

Chunghun et al. [11] provided a mathematical definition of supply chain reliability and relevant functions based on traditional reliability theory. This definition is then applied to basic structural reliability models for diverse types of supply chains. Thereafter the paper verified the proposed functions and structural reliability models were applicable to several types of supply chains through application to a case study supply chain. Consequently, a unified framework for quantifying the reliability and resiliency of almost any supply chain was developed. The framework allowed for modeling of actionable strategies for improving the reliability and resiliency of supply chains.

Because of their perceived lack of a validated measurement model, Chowdhury and Quaddus [12] developed a measurement instrument for SCR. Their work involved a qualitative field study followed by a quantitative survey. They employed content analysis to explain various dimensions in the qualitative field study. Then they used a partial least squares-based structural equation model to analyze the data collected in the quantitative study. The resultant measurement model is a multidimensional and hierarchical construct that consists of three dimensions—proactive capability, reactive capability, and supply chain design quality.

Khan et al. [6] used questionnaires from 434 disaster relief workers to derive a model of how emerging digital technologies can mediate and make more transparent humanitarian logistics (HL) sustainability. The study results suggest that in disaster relief operations, emerging technologies can be a way forward for achieving system transparency and HL sustainability, thereby reducing corruption and mismanagement in HL.

2.2. Innovative SCR Studies

Various articles discussed different factors impacting SCR such as technology, the environment, and natural resources as well as governance mechanisms. These articles are summarized next.

De Vass et al. [13] used grounded theory to study the effects of the Internet of Things (IoT) on supply chains. They found that the IoT improved the following: visibility of goods movement, data capture, partner communication, and business intelligence. Nevertheless, retailers faced challenges due to lack of top management initiative, new technology acquisition cost, stakeholders' reluctance to accept change, unwillingness to share data, and inadequate interoperability between partner systems. Indeed, the IoT contributed to higher SCR through increased real-time information, which could enable a component to be seen as beginning to fail so it could be repaired before actual failure occurred. The study results are a 'proof of concept' that there are tangible IoT benefits that strengthen IoT-related investment decisions. Rajesh [14] used a Total Interpretive Structural Model (TISM) to analyze SCR taken in relation to technological capabilities. After the development of a TISM, he did a case study to validate his model. What he found was that the most influential technological capability is the capability to modify supply chain design and planning capabilities.

Paksoy et al. [15] created a nonlinear integer programming model of a supply chain that utilized concepts from balancing an assembly line. The model's purpose was to optimize the design of a supply chain, considering total costs and number of supply chain components. Koc [16] created an evolutionary algorithm for supply chain network design that involved the concept of assembly line balancing.

Wu and Pagell [17] addressed the need for environmental and natural resource studies to be integrated with the more traditional profit-focused business models. How to balance short-term profitability with long-term environmental sustainability when making supply chain decisions while accommodating uncertainty was their focus. They postulated five sets of propositions that explain how exemplars in green supply chain management are made and they identified four environmental postures that help explain the decisions organizations make when dealing with strategic trade-offs among the economic, environmental, and social elements of the triple-bottom line.

Fujimoto and Park [18] evaluated the Great East Japan Earthquake and endeavored to design a supply chain for competitiveness and robustness considering such disruptions. They did this through "virtual dual sourcing" in which a firm facing supply chain disruptions caused by a disaster carefully chooses either to quickly recover a damaged component or transfer critical design information to a substitute component. Chen et al. [19] addressed the key question of how supply chain reliability and resilience should be quantified. They suggested existing methods do not (1) adequately represent the interdependencies between different supply chain nodes and (2) do not allow for the modeling of actionable decisions and cannot be used to direct improvement strategies. Tan et al. [3] developed a graph-based model to measure structural redundancy for SCR. Supply chains were found to be increasingly vulnerable because of globalization and lean initiatives. To improve SCR, these researchers proposed supply chain redundancy. Their paper presented a conceptual model of a supply chain network using graph theory, considering the relationships between plants and materials. Their model showed that increasing structural redundancy of the supply chain network improves SCR against disruptions.

Gong et al. [20] presented a social system theory perspective on multi-tier sustainable supply chain management. They found that focal companies tend to create both internal complexity and collaborative complexity using a variety of governance mechanisms. The article provided an in-depth understanding of nuanced mechanisms of managing different tiers of suppliers to cope with complexities by adopting a social systems perspective. Ivanov and Dolgui [21] studied Low-Certainty-Need (LCN) supply chains and developed a new perspective in managing disruption risks and resilience. They identified an LCN supply chain framework, concepts and technologies for its implementation, as well as missing themes and new research questions that contribute to a better understanding of SCD risks. Li et al. [22] studied how network characteristics affect SCR under conditions of risk propagation. They found that network characteristics can lead to a better understanding of SCR than supply chain network types. They showed through simulation that a reduced list of key network characteristics can lead to as good a result as a complete list of network characteristics. They used a case study to illustrate how their approach helped to better understand SCR. Finally, they summarized key points that described how key network characteristics affect SCR.

Sokolov et al. [23] studied the structural quantification of the ripple effect in supply chains. The ripple effect arises whenever there are disruptions, vulnerability, or instability in supply chains. Their goal was to quantify the ripple effect arising from a structural perspective. The results of their research can assist decision makers in the selection of a proper supply chain design that is resilient and stable. Jain et al. [24] developed a hierarchy-based model for SCR, explaining the dynamics between various enablers and validating the model empirically. They began by identifying enablers and then used experts to construct an interpretive structural model (ISM). They then constructed and tested a hypothesis for each and every edge in the ISM. Using 105 test cases they were able to validate every relationship in the ISM as being either strongly supported or supported. They learned that information sharing is important for trust and for supply chain visibility and minimizing uncertainty. They further learned that all these enablers ultimately lead to their top-level enabler adaptive capability.

Khan et al. [25] studied and analyzed the effect of digital technologies on the supply chain for traceability and for creating transparency. The study findings suggest that the emerging digital technologies will enhance the traceability and transparency of the supply chain. Ivanov et al. [26] discussed a variety of emerging technologies and how they can be used to anticipate and prevent supply chain disruptions. Digital technologies such as Industry 4.0, IoT, business analytics, artificial intelligence, and advanced tracking and tracing technologies enable supply chains to be more visible, thereby allowing possible disruptions to be detected and repaired before they actually occur. However, the paper says nothing about how to conduct an adaptive response project after a disruption actually occurs. Ransikarbum and Mason [7] presented and provided results derived from an algorithm for finding near-optimal solution strategies to the SCD problem. However, they did not provide direction as to how the selected adaptive response project should be executed. Such is the purpose of this paper.

2.3. Systematic Literature Review Articles

Many researchers have carried out systematic literature reviews on most aspects of SCR. Several of those articles are discussed here.

Sawyerr and Harrison [27] performed two systematic literature reviews to identify the prescribed formative elements of SCR to compare them with the unique characteristics of high-reliability organizations (HROs) and to derive lessons useful for improving SCR. One such formative element absent in the SCR literature was the managerial commitment that was exhibited in high-reliability organizations. Moreover, Sawyerr and Harrison [27] found that the most cited characteristic of HROs, namely their flexible decision-making structure, was pointed out as a prima lesson towards developing resilience in supply chains. Singh et al. [28] discussed how changes in customer interests and demands increase the risk of disruption in supply chains and hence the need for increased SCR. A systematic literature review, analysis, and classification revealed 17 performance indicators. An SCR framework was developed using these indicators that should facilitate supply chain managers in examining and withstanding disruptions.

Liao and Widowati [29] performed an extensive review of supply chain theoretical models from the years 2014 to 2019. Some 97 articles were cited from 48 journals in 25 categories. The study categorized past studies of supply chain management and identified differences while indicating possible future developments in the study of supply chain management. Hosseini et al. [30] reviewed quantitative methods for SCR analysis and focused on the original concept of resilience capacity. They identified missing areas of SCR research related to withstanding, adapting, and recovering from disruptions in supply chains. This in turn led to the discovery of future opportunities for SCR research.

Leuschner et al. [31] conducted a systematic literature review on the topic of Supply Chain Integration (SCI) involving 17,467 observations. They found support for SCI having a positive impact on firm performance. Their research indicates that there is a positive and significant correlation between SCI and firm performance. Ates et al. [32] conducted empirical studies on the link between supply chain complexity and firm performance. Prior studies determined that supply chain complexity was detrimental to firm performance, while Ates et al. [32] found that supply chain complexity has a negative effect on operational performance but a positive effect on the firms' innovation and financial performance. By distinguishing between different levels of the supply chain, they observed nuanced findings.

2.4. SCR Taken in Relation to TOC and CCPM

Kim and Mackenzie [33] were among the first to endeavor to understand potential bottlenecks in relation to SCR. Sakib et al. [34] created a probability model of supply chain disruption and disaster. Filho et al. [35] performed a critical analysis of TOC methods and the potential implementation of TOC concepts in the management of distribution, specifically distribution logistics. Filho et al. [35] showed that TOC could be used to analyze the logistics of firms and thus improve their SCR. Modi et al. [36] utilized TOC to revolutionize supply chain management in a case study.

Rahman [37] studied the factors influencing the performance of supply chains using Goldratt's Theory of Constraints Thinking Process (TOCTP), as discussed in [38–40]. Rahman [37] applied the TOCTP not only to identify critical success factors in supply chain management but also to understand causal relationships among these factors. The study determined that understanding the dynamic nature of supply chains through cause-and-effect relationships is critical to the formulation of supply chain growth strategies.

Ghorbani et al. [41] used the TOCTP [38–40] to analyze a cellular manufacturing system. Their research tool was the Current Reality Tree, one of five components that make up the TOCTP. Jo et al. [42] used Goldratt's [43] CCPM concepts to suggest expanded deployment of resource buffers that prevent delays in pipeline projects. They observed that cost overruns and schedule delays were commonplace in such projects because of delays in the pipeline material arrival and installation. Their simulation results showed that the use of CCPM coupled with resource buffers were able to reduce the duration of pipeline projects by about 35% when compared to traditional methods. Costs were comparably diminished. Their study demonstrated that proactive materials management coupled with CCPM can eliminate pipeline installation project extensions, develop schedule-based risk mitigation measures prior to installation, and enable project teams to efficiently manage limited human and material resources.

Appiah et al. [44] studied the lack of adequate working capital for Small-to-Medium-Enterprises (SMEs) in Ghana, using TOC and data from 497 SMEs. The data were used to test nine hypotheses regarding the lack of funding availability for this industry in terms of constraints on the growth of the industry. They found that high levels of competition, high corruption perception, absence of policy awareness, inadequate external credit facilities, inadequate information, inadequate managerial capabilities, and inferior technological capabilities all contributed to a lack of investment capital needed to move this industry forward and improve its SCR.

Finally, Kahn et al. [45] provided a very interesting result involving applications of covariance-based structural equation modeling to HL that demonstrates the importance public trust plays in enhancing the performance, efficiency, and effectiveness of HL derived from disclosure, clarity, accuracy, corporate governance, decision making, and accountability. The study raised awareness of the need to carefully evaluate decisions related to the fair distribution of relief items. Performance, efficiency, and effectiveness of SCR (closely related to HL) are what this study is about.

As Table 1 would suggest, none of articles concern themselves with the repercussions coming forth from the disruption, nor do they have any interest in the post-disruption adaptive response projects that must follow.

Table 1. Categories of articles found in the SCR literature.

Topic	References No.
Definitions, frameworks, measures	[5,6,9–12]
Innovative SCR studies	[7,13–26]
Systematic literature review articles	[27–32]
SCR taken in relation to TOC and CCPM	[33–44]
Post-disruption adaptive response projects	None we can find

Many of these studies suggested that the trends toward global sourcing and the concepts of lean systems have made supply chains fragile instead of robust when it comes to resiliency. Most of these studies do not reflect an interest in the production capacity consequences of a disruption nor do they express any interest in the recovery project(s) that must follow. Thus, this research is focused on disruption prevention through robust and resilient supply chain structures and on the production capacity consequences of a disruption that drive the subsequent follow-up projects. Finally, this research is focused on the follow-up projects themselves, that is, how to speed up their completion.

3. Models and Analysis

In this section, supply chain structural and reliability models are considered in which the endeavor is to understand how the supply chain structure can be changed so resilience can be improved. The results of the structural and reliability models are then used within bottleneck simulations and scenarios to derive and deduce the contributions of the research. The approach taken is pragmatic and practical rather than theoretical. Resilience itself here is handled in a practical and pragmatic way. For example, our measures of resilience are risk-related—the reliability of the supply chain and hence of each component and the impact should a component fail. As in any risk analysis, the endeavor is to identify the risk event to determine its failure probability (i.e., its reliability) and the magnitude of a failure impact for each risk event studied. We are particularly focused on how these risk events relate to the structure or topology of supply chains. The major components of a simple supply chain are typified in Figure 1.

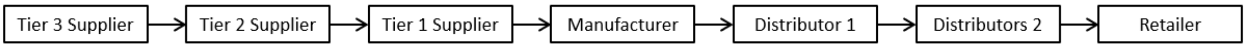

Figure 1. The generic sequential supply chain.

For the simple supply chain structure shown in Figure 1, the component with the least capacity is the bottleneck component that determines the capacity of the entire supply chain. Simple sequential supply chains, like the one shown in Figure 1, have production dynamics that are like that of assembly lines in which the bottleneck workstation determines the capacity of the entire assembly line. These supply chains are the simplest to understand. If any one of the components goes down, the entire supply chain is disrupted and therefore un-sustained. So, each component is considered a single point of failure. The overall reliability of the entire supply chain is simply the multiplication of the individual component reliabilities:

$$R_s = R_1 * R_2 * \ldots . * R_n, \tag{1}$$

where R_s is the supply chain reliability, R_1, R_2, ... R_n are the individual component reliabilities that are in series.

Suppose each component in Figure 1 has a reliability of 0.9. Then, the overall system reliability of the sequence of seven would be

$$R_s = (0.9)^7 = 0.478297. \tag{2}$$

This would mean that for any given year (365 days), the supply chain would be up and running only 174.6 days. If each component in Figure 1 had a reliability of 0.985, the entire supply chain would have an overall reliability of 0.9 (0.899609, actually). That would mean that for any 365-day year, the supply chain would not be running for 36.5 of those days, or roughly 3 days out of each month. Clearly, very high individual component reliabilities are needed to achieve six-sigma reliability (3.4 min of downtime in every million minutes = 694 days).

Another topology is shown in Figure 2. This structure is far more reliable because there are several retailers for the customer to buy the product from. If one retailer does not have the product, another retailer might.

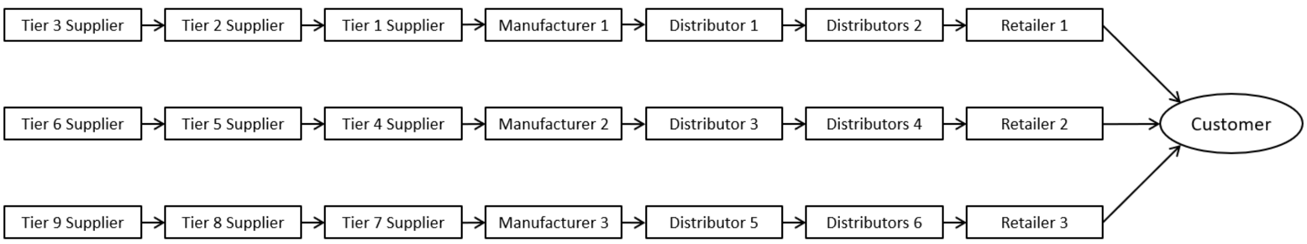

Figure 2. A multi-sequence supply chain.

In Figure 2, the customer has three different retailers that s/he could buy the product from. This redundancy greatly increases the reliability of the overall supply chain—that reliability being measured by the likelihood of the customer being able to purchase the product. Assume for the moment that the supply chain depicted in Figure 1 had an overall reliability of 0.9. Then, the reliability of the supply chain in Figure 2 would be the equivalent of three of the supply chains shown in Figure 1 in parallel. If each retailer (each individual supply chain string) has a reliability of 0.9, the overall system reliability is 0.989. The actual formula is

$$R_s = 3R_r - 3{R_r}^2 + {R_r}^3, \tag{3}$$

where R_r is the reliability of each supply chain string (assumed to be identical and equal to 0.9).

As we learned in Figure 1, each component in Figure 2 must have a reliability of 0.985 for each supply chain string to have a reliability of 0.9.

When a supply chain component goes down, it can take the entire string to a halt. For example, in Figure 2, assume Manufacturer 2 goes down. Then, after a period, Retailer 2 cannot sell and deliver the product(s) produced by the supply chain string. All three strings must compensate. Strings 1 and 3 can do this through increases in their component capacities. How quickly they can do this becomes the paramount concern.

In terms of network topology, breadth-first supply chains are more reliable than depth-first ones. The supply chains shown in Figures 1 and 2 are depth-first supply chains. Breadth-first supply chains are shallow and very spread out, more like the supply chains we find in services. A more complex supply chain (akin to breadth-first) would be that shown in Figure 3.

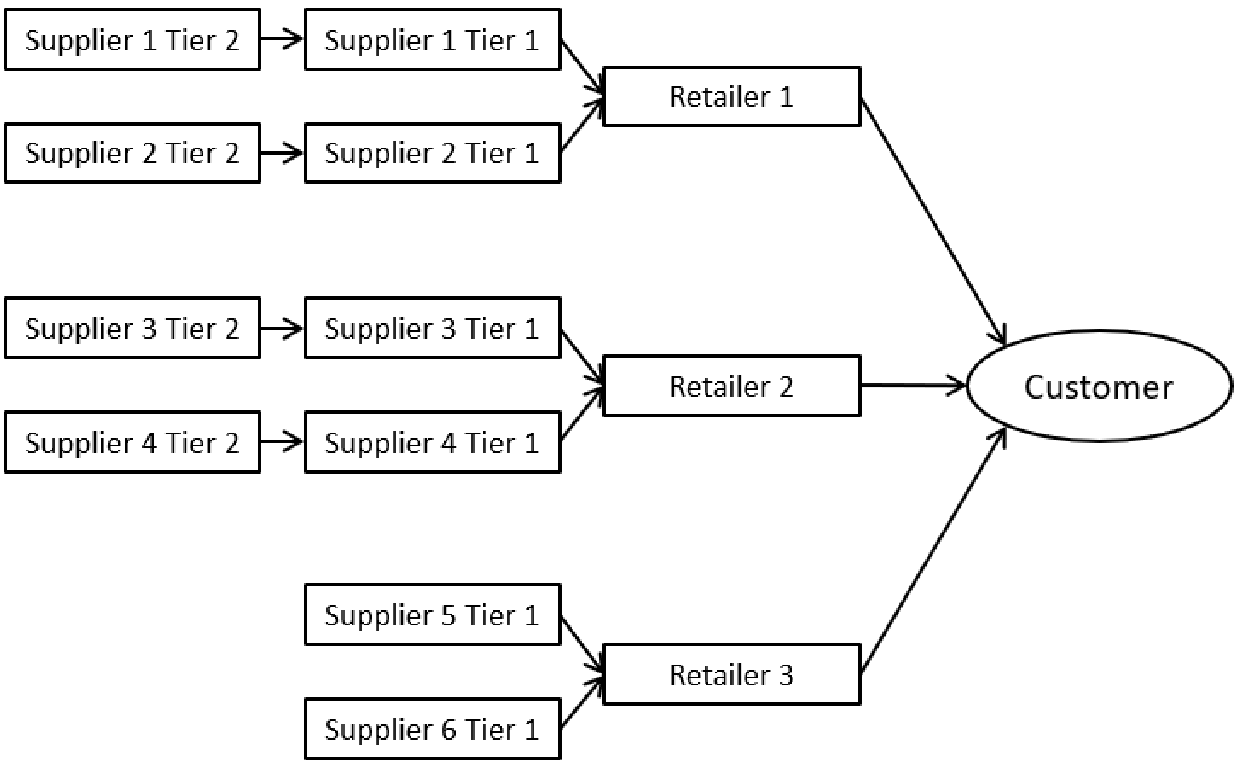

Figure 3. A breadth-first supply chain.

The reliability of these supply chains might be alternatively modeled as conditional reliabilities. Let A and B represent two successive components in series. Then let R(A.B) be the joint reliability of these two components taken together. Clearly,

$$R(A.B) = R(A/B) * R(B) = R(B/A) * R(A). \tag{4}$$

If the reliabilities of A and B are completely independent, then:

$$R(A/B) = R(A) \tag{5}$$

$$\text{and } R(B/A) = R(B). \tag{6}$$

The independence of A and B would make:

$$R(A.B) = R(A) * R(B) = R(B) * R(A). \tag{7}$$

This, of course, is the underlying assumption of the reliabilities that are calculated for Figures 1 and 2.

Assume all retailers in Figure 2 supply the same amount to their customer base. In the case of the supply chains in Figures 2 and 3, if one of the three supply chain strings should go down, the other two would still be running. The question becomes whether they can increase their capacities fast enough to compensate for the downed supply chain string. To have a constant supply chain capacity, the capacities of the two remaining supply chain strings would have to be increased each by 50% to compensate for the downed supply chain string. How quickly they can do this becomes the issue at hand. All three supply chains are competing to see who can be first to replace the lost capacity. For that reason, we address the issue of increasing supply chain capacity next.

Suppose the capacity of the entire supply chain shown in Figure 2 above was 3000 units/week. Assume further that each supply chain string can produce 1000 units/week. If one string goes down, the capacities of the other two must increase their capacities from 1000 units/week to 1500 units/week. To sustain a capacity of 3000 units/week, then, the remaining two strings must increase their capacities by 50%. Alternatively, the disrupted supply chain string may be able to quickly restore its downed component before the competing supply chains can increase their capacities.

Consider the problematic supply chain exhibited in Figure 4. If the Tier 1 Supplier goes down, it could take the entire supply chain down. What does this do to the overall reliability of the entire supply chain? The Tier 1 Supplier is a single point of failure for the entire supply chain. In Figure 2, its reliability is assumed to be 0.985. In addition, in Figure 2, the reliability of the entire supply chain is calculated to be 0.989. It appears that the reliability of the entire supply chain string is reduced to 0.985 as the Tier 1 Supplier becomes the 'bottleneck' in terms of the total supply chain reliability.

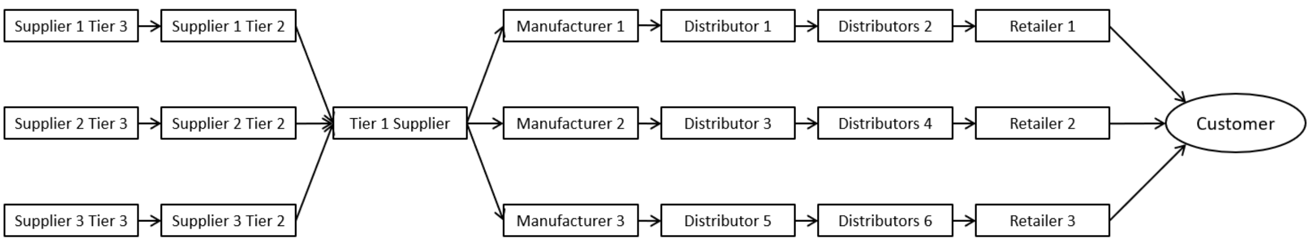

Figure 4. Multiple supply chains sharing the same supplier.

This problem becomes more acute when the supply chain is much shorter, as in service system supply chains. Once again, we will assume three retailers as in Figures 2–4. Consider the supply chain configured as in Figure 5, where the strings are only three components long, but once again there is a shared component between the three supply chain strings, as in Figure 4.

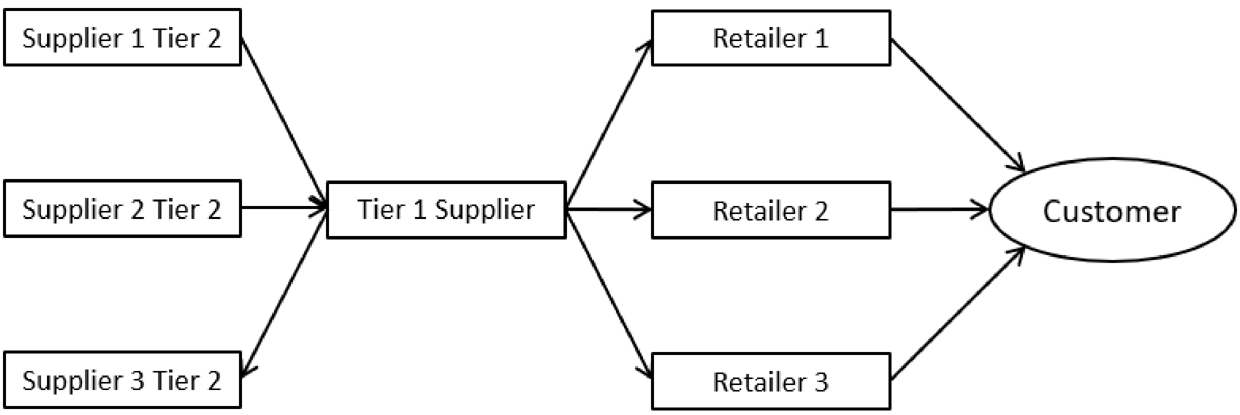

Figure 5. A shared component within a collection of three two-tier supply chain strings.

Now the reliability of each component must be only 0.9655. This will create a string reliability of 0.9 for each of the three strings, which when combined using the formula in Equation (3) will give us an overall system reliability of 0.985. This would be true only if the Tier 1 Supplier was not shared; however, because it is shared, it becomes a single point of failure for the entire supply chain, reducing the reliability of the entire system to the assumed reliability of the Tier 1 Supplier, which is 0.9655. Figures 4 and 5 are not unlike the railroad component of every supply chain in the US. If the railroad unions strike, that event would be a single point of failure and bring down most of the supply chains. In the interests of economy and efficiencies, most supply chains have minimal redundancy and engage in sharing suppliers. Twenty years ago, Takata, for example, made failing air bags for twenty percent of the auto industry. Older model BMW, Audi, Honda, Mitsubishi, and Toyota had recalls issued. The National Highway Traffic Safety Administration issued a recall of more than 25 million cars, the largest in US history. This resulted in Takata having to declare bankruptcy.

How to restore the lost capacity quickly is the issue at hand. Lost capacity from disruptions creates the need for restorations that are implemented by adaptive response projects. Quickness depends on the lead times for restoring capacity in the disrupted (failed) component or of all the components in the case of competing supply chains. A look at the differences between the associated lead times of each component reveals some interesting insights into the sustainability of supply chains. It becomes difficult to achieve balanced capacity among the components within the supply chain string when the lead times and capital costs associated with component capacity increases are very different. We will discuss this next.

Reflect on the late December 2022 domestic airline cancellations. This is a type of SCD and is sustainability at its worst. In this case, Southwest Airlines had massive flight cancellations—more than 10,000—in the last two weeks of 2022. Can the other airlines increase their capacities sufficiently fast to compensate? No, they cannot increase their capacities that quickly. You must have additional airplanes (years of lead time), additional pilots (many months of training), additional crews (months to train), more airport gates (years to acquire), etc. This type of disruption is best characterized by Figure 2. One of the three retailers goes down and the other two must compensate if they can. Clearly, this is a capacity issue.

Our purpose here is to explore some major difficulties in increasing the capacity of a supply chain string. When a supply chain component goes down, it may take the entire string down. The rest of the strings may have to compensate by increasing their capacities. The following analysis is intended to show how difficult that is when component lead times and fixed costs are very different from one component to the next. For starters, the component with the longest lead time is most likely the bottleneck component. Suppose all supply chain components begin capacity increase projects on the same date. Assume as well that the bottleneck component determines the capacity of the entire string. Then, the bottleneck component will be the component with the longest lead time, assuming all supply chain components were balanced (equal) in terms of their capacities at the start. Of course, the time horizon must be less than or equal to the longest lead time. If the time horizon exceeds the longest lead time, then depending on how much capacity is added to the component with the longest lead time, it may or may not still be the bottleneck component. This we illustrate with a two-component supply chain string in Figure 6. The models exhibited in Figure 6 assume deterministic demand, constant lead times, that every part, product, item, or service can get to the customer end of the supply chain only by going through every component of the simple, sequential supply chain. Finally, at the start of the capacity increase initiative (adaptive response project), it is assumed that all component capacities are in steady state, meaning all component capacities are roughly the same.

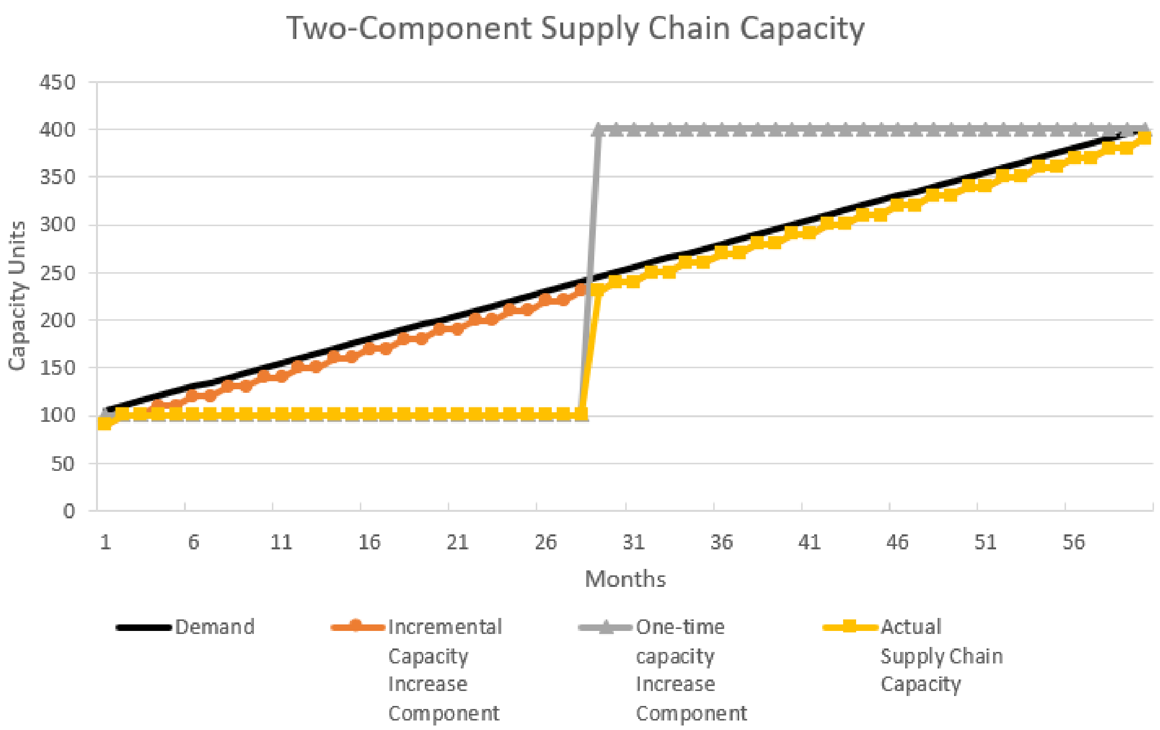

Figure 6. Component capacity increases and their constituent effects upon the capacity of the two-component supply chain.

Consider a supply chain with just two components in series. One of these can increase its capacity in small increments rapidly. The second of these requires two and a half years to increase its capacity and when it does so, it quadruples its capacity, after which its capacity stays constant for the remaining 30 months.

Consider the time chart of capacity increases in Figure 6. The chart shows the growth of a sequential supply chain consisting of just two components. Time is exhibited for a period of 5 years or 60 months. The black line without symbols is the actual demand. The gray line with triangles is the growth of a one-time capacity increase component. The orange line with circles is the growth of an incremental capacity increase component. The yellow line with squares in Figure 6 represents total supply chain capacity. Total supply chain capacity is equal to the capacity of the component whose capacity is smallest, i.e., the bottleneck component. From months 1 through 30, there is no change in the one-time capacity increase component, as it is assumed to take 30 months to complete a new plant, such as a wafer fab, an auto factory, a refinery, or a pipeline. It is assumed that the one-time capacity increase component has a lead time of 30 months or 2.5 years. Notice that actual demand is increasingly under-served during the first 30 months.

After the first 30 months, total supply chain capacity follows the capacity of the bottleneck component, which is the incremental capacity increase component. It is assumed that when the one-time capacity increase component becomes operational, its capacity is quadrupled. Once the one-time capacity increase component becomes operational with the increased capacity, then the incremental increase component becomes the limiting bottleneck component that determines total supply chain capacity.

Consider the four-component supply chain whose structure is shown in Figure 7 and whose capacity growth is shown over 60 months in Figure 8. In Figure 7, the first and fourth components (Tier 1 Supplier and Retailer) can increase their capacities incrementally and rapidly, while the second and third components (Manufacturer and Distributor) have long lead times and high initial costs associated with their capacity increases.

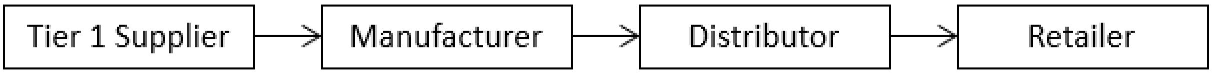

Figure 7. Four-component supply chain in which the first and fourth components (Tier 1 Supplier and Retailer) can increase their capacities incrementally and rapidly, while the second and third components (Manufacturer and Distributor) have long lead times and high initial fixed costs associated with their capacity increases.

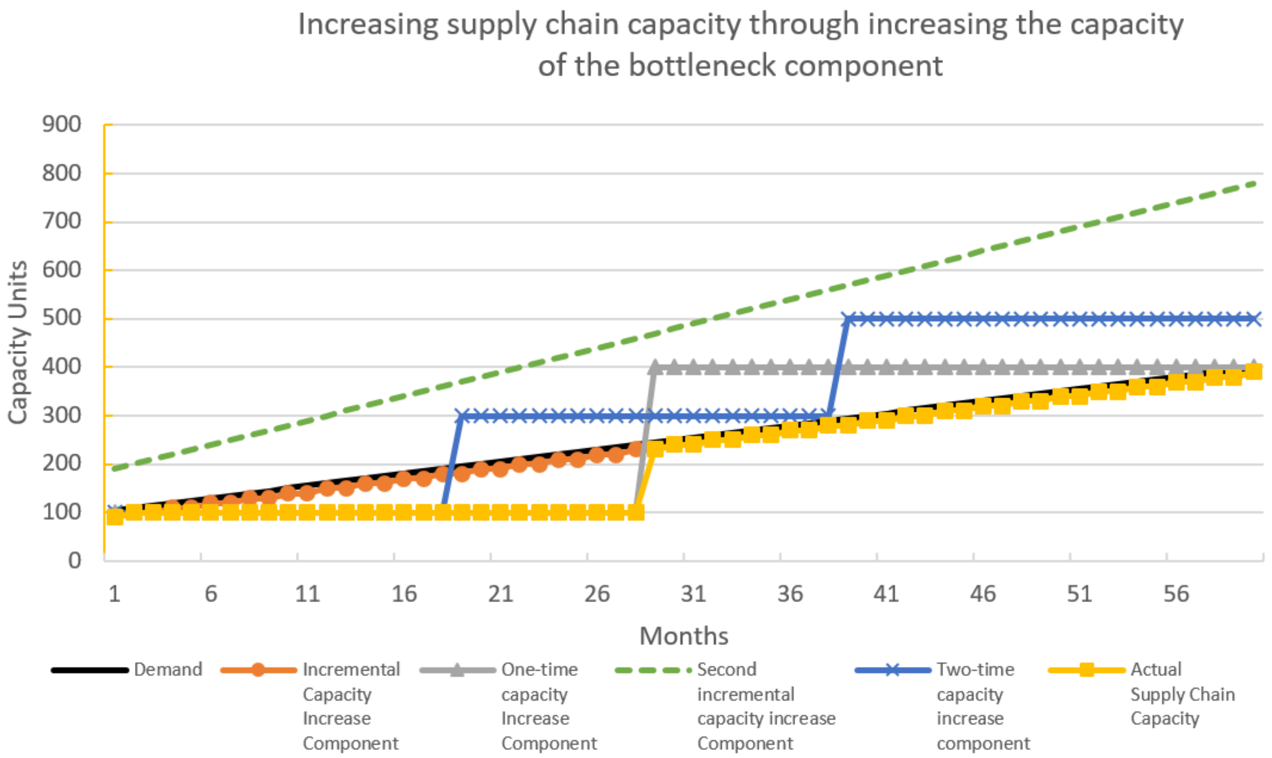

Figure 8. Component capacity increases and their constituent effects upon the capacity of the entire four-component supply chain.

The growing capacities of these four components shown in Figure 7 along with the capacity of the entire supply chain are depicted below in Figure 8, a simulation of the growth in each of the four components. The models in Figure 8 assume the same assumptions as of those of in Figure 6 like deterministic demand, constant lead times and such.

Here we see a discrepancy in the capacities of the various components leading to significant inefficiencies in the operation of the entire supply chain. The first component (Tier 1 Supplier, shown in orange with circles on the line) grows slowly and incrementally. The second component (Manufacturer, shown in gray with triangles) increases its capacity four-fold and only once during the 60-month period. For the first 30 months it (the Manufacturer) is the bottleneck component. For the second 30 months, the first component (Tier 1 Supplier) is the bottleneck. The fourth component (Retailer, shown as a dashed line in green) has a capacity that far exceeds the rest of the supply chain. The Retailer component is never the bottleneck. Similarly, the two-time capacity increase component (Distributor 1, shown in blue with 'x's on the line) is the bottleneck component during the first 18 months of the simulation. The actual supply chain capacity is the yellow line with squares on it.

What these simulation scenarios show us is that we must understand where the bottleneck component in the capacity of a supply chain is and then focus on increasing the capacity of that bottleneck until some other component becomes the bottleneck. This is exactly what Goldratt's [8] TOC tells us.

Furthermore, the simulation/scenarios in Figures 6 and 8 show that when component capacities are comparable and the supply chain needs to increase its capacity, the bottleneck component is the component with the longest lead time. This informs the decision maker which component(s) to focus on. In what follows, we shall endeavor to prove these concepts with logic. Let us start with a definition of a bottleneck taken in the context of a supply chain string.

A bottleneck, by definition, is the component that limits, constrains, or determines the capacity of the supply chain string. The bottleneck is the component with the lowest throughput in terms of units completed per time period. From this definition, the following theorem is a simple deductive consequence.

Theorem 1. *The component that determines the capacity of the simple, sequential supply chain string is the bottleneck component.*

Proof. The proof is by tautology—a straightforward consequence of the definition of a bottleneck. In this theorem we have taken the definition of 'bottleneck' and inverted it. Q.E.D. □

Lemma 1. *In a simple, sequential supply chain string that is endeavoring to increase its capacity, the component that has the least capacity (least throughput) is the bottleneck.*

Proof. The proof is by contradiction. Assume the opposite—namely that the component with the largest capacity is the bottleneck. Such could never be the case because the throughput of the largest-capacity component can produce at rates larger than the other components. The largest-capacity component would build up a queue of items waiting for its successor. Meanwhile, it is idle much of the time, waiting for its predecessor to create items for it to work on. Certainly, it is not the component other components are waiting on and thus, it is not the bottleneck. Likewise, no other component could be the bottleneck; only the component with the least capacity is the bottleneck. Q.E.D. □

Theorem 2. *When supply chain component capacities are roughly the same and demand has suddenly increased because of an SCD somewhere else in the supply chain, then the bottleneck component will be the one with the longest lead time until that lead time is exceeded in real time.*

Proof. Assume that, initially, all component capacities are comparable. Logically, the way to proceed is to increase the capacity of all components whose capacities are insufficient. The component whose capacity increase will be slowest will be the bottleneck; all the other components will be waiting on that component with the longest lead time required to increase its capacity. Thus, the component whose capacity increase is slowest will be the one whose capacity increase lead time is longest. That component will be the bottleneck until real time exceeds the lead time of that component. This was illustrated in Figures 6 and 8. Q.E.D. □

Theorem 3. *The component that determines the capacity of the supply chain string will be the one with the longest capacity increase lead time, assuming all capacities are roughly the same at the time the capacity increase initiative starts.*

Proof. The proof is a straightforward consequence of Theorems 1 and 2. Q.E.D. □

Theorem 4. *The component with the longest capacity increase lead time is the bottleneck in any supply chain string, assuming all components start out with roughly the same capacity.*

Proof. The proof is just a tautology—a straightforward consequence of the definition of bottleneck and Theorem 3. Q.E.D. □

These simulation/scenarios and their associated lemmas, theorems, and proofs inform the supply chain decision maker as to where to begin the project of increasing the capacity of a supply chain string. They along with the rest of the material in this paper suggest what components the manager should be most focused on in terms of reliability of the supply chain string. These insightful contributions can greatly assist supply chain decision makers in their endeavor to reduce the likelihood and impact of an SCD in a supply chain string. These contributions can also assist in the creation of contingency plans.

4. Discussion

Firms must be aware of their supply chain disruption vulnerabilities and execute solutions to attenuate these identified risks. The possibilities are to eliminate the risk, avoid the risk by using another more reliable supplier, transfer the risk, or simply assume the risk. In situations where the risk cannot be eliminated, avoided, or transferred, it must be assumed. In such cases, the firm must have contingency plans in place. Those plans usually involve fast execution of adaptive response projects when a disruption occurs.

From the simulation scenarios in Figures 6 and 8, we see that rapid mitigation of a major SCD can be difficult, expensive, and time-consuming. The restoration of steady-state capacity can be accomplished by the disrupted firm or by one or more of its competitors. A competitor may decide its supply chain components can be more quickly expanded than the time it takes to repair the disrupted SC. In any case, such mitigation involves fast execution of adaptive response projects. Such projects are under terrific duress to be finished as fast as possible and at minimal cost. A flowchart of the sequence of steps firms must use to become more resilient is shown in Figure 9. The outputs of a predecessor step become the inputs to the successor.

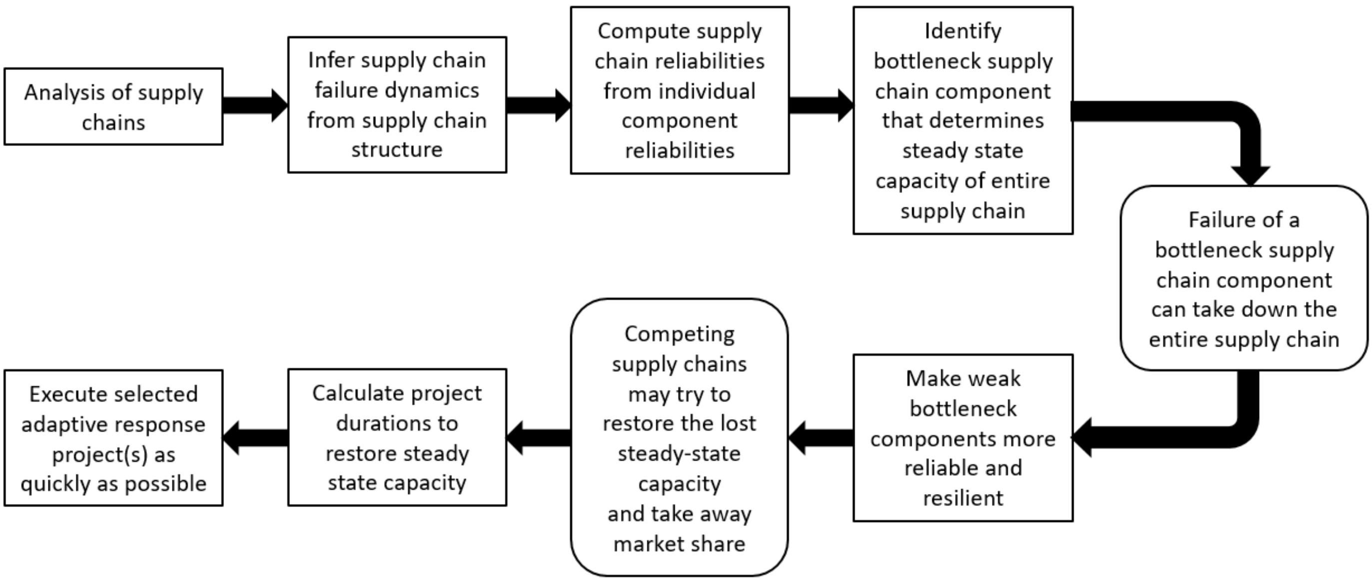

Figure 9. A flowchart of the sequence of steps firms must use to become more supply chain-resilient. Refer to Analysis of supply chains in Figures 1–5; Infer supply chain failure dynamics from supply chain structure in Figures 6 and 8, and Compute supply chain reliabilities from individual components reliabilities in Equations (1)–(7).

5. Managerial Implications

Quality gurus like W. Edwards Deming [46] encouraged firms to use just a few suppliers for any one material item. One reason for this is because it gives the firm an opportunity to build learning relationships with those few suppliers. The problem with this strategy is that if the number of suppliers reduces to two or less, then there is a high probability of an SCD, as reliabilities will decline due to the lack of redundancy.

The models presented here make a case for fast execution of adaptive response projects. So, what are the techniques for fast execution of projects? Companies must have well-rehearsed, fast-execution contingency project plans and funds in place to quickly accomplish a solution to a major supply chain disruption. Below is a list of techniques for fast execution of projects that will shorten their durations.

1. *Accelerated requirements determination*—the ability to quickly determine the cause of the disruption and its solution.
2. *Accelerated project schedule and budget determination*—the competence to quickly and accurately determine a project schedule and budget that will guide project execution.
3. *Adding resources at the beginning of the project*—more project personnel usually means projects are finished more quickly.
4. *Outsourcing project work*—when outside resources can do all or part of the work more quickly than doing the work in-house, it makes sense to outsource.
5. *Scheduling overtime*—allowing project personnel to work long hours to expedite the work.
6. *Using concurrency*—allowing for as much of the work as possible to be done during the same time period, i.e., in parallel.
7. *Establishing a dedicated project team*—requiring the personnel assigned to the project to do nothing but the project until it is completed.
8. *Crashing the project*—a technique that is discussed in operations and project management texts [1,2,47] that shortens the duration of projects.
9. *Improve the efficiency of the project team*—using consultants to train the project team.
10. *Fast-tracking*—pulling work off the critical path; starting work before all predecessor work is complete.
11. *Reducing project scope*—do nothing but the absolute minimum work required to re-establish lost capacity.
12. *Use CCPM concepts*—Critical Chain [43] concepts can greatly reduce the time required to complete projects.

It is the last technique (CCPM) listed above that the authors are particularly fond of in this context. Done right, CCPM gets adaptive response projects finished superfast and at little additional cost. While a detailed discussion of CCPM is beyond the scope of this article, there are many very useful tomes and articles discussing successful executions of the technique [42,43].

6. Conclusions

In this paper, capacity and project perspectives are applied to the issues of SCD and SCR. Nothing in the literature review would suggest that this has ever been done before. When a supply chain component goes down, it can take the entire supply chain down. What happens after that is supply chain personnel scramble to compensate for the lost capacity. This represents an opportunity for competing supply chains to pick up market share and increase their revenues and profits. How quickly they can do that depends on the lead times of the various components whose capacities must be increased. This paper has endeavored to illustrate why rapid capacity increases may be necessary to maintain sustainability in a competitive environment. Disruptions in supply chains are compensated using projects which repair existing defective supply chain components or which generate new ones, resulting in a return to adequate capacity or steady state. Competitors may see this disruption as an opportunity to take market share away from the firm whose supply chain is disrupted. To do this, the competing firms must execute adaptive response projects quickly. How to execute adaptive response projects quickly does not get much attention in the SCR literature, but we have addressed this issue in this paper.

The paper opens an entire field of new SCR research directions—how to repair/replace disrupted supply chain components faster, how to anticipate and prepare for a possible SCD, and so forth. The article takes a new perspective on SCD, namely the loss of supply chain capacity and how that can be addressed by both the disrupted supply chain and by competitors wanting to capture market share. Finally, the article suggests new opportunities for the study of accelerated, adaptive response projects to remedy disruptions, a field in which there appear to be almost no contributions so far.

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