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# **Supply Chain Disruption and Agent-Based Modeling**

## **A Literature Review and Model**



Douglas Thomas  
Jennifer Helgeson  
Ireland Crowther

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**Supply Chain Disruption and Agent-Based Modeling**

*A Literature Review and Model*

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## **Abstract**

This report provides a literature review of supply chain disruption and agent-based models. It also develops an agent-based model proof of concept to examine emergent phenomena in supply chain disruption. This model will eventually be used to 1) examine how supply chain disruptions might propagate downstream, demonstrating the findings of previous papers and 2) identify emergent behavior or patterns in supply chains as it relates to disruptions. Supply chain disruption can be classified by scale (micro vs macro), chronology (short-term vs long-term), and point-of-loss (upstream vs downstream). There is a literature gap relating to macro short-term downstream losses; that is, there is a literature gap in understanding the aggregated losses that occur when goods fail to arrive at the next point in the supply chain. There is also a limited understanding of the frequency and magnitude of supply chain disruptions that makes it difficult to estimate annualized losses, which are useful for guiding investment in mitigation. Finally, there is a literature gap in understanding supply chains from a network-level perspective. This report presents a flexible agent-based model that allows various aspects of the model to fluctuate, including the number of tiers, establishment per tier, products per tier, flow time, substitutability, and potentially other aspects. This flexibility allows for the exploration of diverse supply chain structures and supports network-based analysis—addressing the gap identified in the existing literature. The model further facilitates examining other establishment characteristics (e.g., inventory level) to understand how they interact with network design.

## **Keywords**

Agent-based model; disruption; loss; manufacturing; modeling; supply chain

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## 1. Introduction

### 1.1. Background

Supply chains are becoming increasingly interconnected in a global economy where even minor disruptions can have extensive consequences, leading to delays, increased costs, and supply shortages. It is important to understand the patterns, sources, and impacts of supply chain disruptions to facilitate efficiency. Many are increasingly recognizing the importance of understanding disruptions in supply chain networks; however, as stated by Kim et al., supply chain literature “still lacks a clear conceptualization of a network-level understanding of supply disruptions” [4].

There are several recent examples of major supply chain disruptions spanning natural, human-made, and biological causes. In each case it is well beyond the scope of a single firm or actor to prepare for, mitigate, or respond to such a supply chain disruption. Currently, there is limited understanding regarding the ideal investments/strategies to mitigate the effects of a disruption in national supply chains, including those at the industry and firm level. A number of studies examine economy wide losses that result from supply chain disruption; however, there are limitations to many of these, as some of the approaches (e.g., input-output analysis or computable general equilibrium models) tend to exclude the short-term downstream losses such as those that occur when goods fail to arrive at the next step of the supply chain. Previous research by two of the authors of this report, Thomas and Helgeson [1][2], investigated the short-term downstream effects of natural hazards, which includes the more immediate effects. They find that during the 2005 to 2016 time period, manufacturing GDP was suppressed by 3.9 % due to hazards upstream – that is, due to hazards experienced by suppliers. This can create an incentive misalignment, as the establishment that invests in mitigation efforts and experiences the hazard locally does not directly experience a large portion of the net benefit. The result may be an underinvestment in hazard resilience. More importantly, these losses would not be included in many analyses of supply chain disruption loss.

Another paper that examines short-term downstream effects is by Thomas and Fung, which measures observations of value added before and after power disturbances to examine the indirect impacts to downstream firms in the supply chain [3]. These impacts are measured across the supply chains of four varying industries—manufacturing, durable goods, nondurable goods, and the private industry [3]. The paper finds that power disturbances significantly impact GDP. Losses can be categorized by their position in the supply chain—affecting directly impacted firms, their suppliers (upstream), and their customers (downstream)—and by their timing, with short-term and long-term effects. Again, these losses would not be included in many analyses of supply chain disruption loss.

This report builds upon the works of Thomas, Helgeson, and Fung discussed above by developing an agent-based model to examine emergent phenomena in supply chain disruption. This model will eventually be used to 1) examine how supply chain disruptions might propagate

downstream, confirming unverified findings of previous papers and 2) identify emergent behavior or patterns in supply chains as it relates to disruptions. The first item involves examining magnitude of losses experienced downstream as compared to that of the establishment that experiences the disruption. The second item involves examining patterns in supply chain simulations that represent generalizable conclusions that might apply to all supply chains. An example of such a conclusion in the literature can be found in studies on the “bullwhip effect,” a phenomenon where small fluctuations in demand cause increasingly larger swings in purchases and inventory levels as one moves through the supply chain.

Agent-based modeling is a computational method used to simulate interactions among autonomous agents within a defined environment. Each agent follows behavioral rules and may adapt in response to changes in the environment or other agents. Agent-based modeling excels in contexts characterized by heterogeneity, nonlinearity, feedback loops, and emergent phenomena—conditions typical of real-world supply chains [5]. Agent-based models provide several distinct advantages in modeling supply chain disruptions:

- **Decentralized Decision-Making:** Agent-based models allow each agent (e.g., suppliers, manufacturers, retailers) to have its own objectives, constraints, and decision rules, reflecting the real diversity in supply chain participants.
- **Modeling Adaptive Behavior:** Agents can respond to disruptions by changing strategies (e.g., re-routing, switching suppliers), making it possible to simulate resilience mechanisms like diversification or agility.
- **Emergent Dynamics:** System-level outcomes (e.g., bottlenecks, bullwhip effects, cascading failures) emerge from bottom-up interactions, which traditional top-down optimization models often miss.
- **Scenario Exploration:** Agent-based models enable experimentation with "what-if" scenarios—e.g., what happens when a port closes or a pandemic disrupts labor markets—helping stakeholders evaluate possible solutions.

## **1.2. Scope**

This report examines the literature on supply chain disruption and the use of agent-based models to better understand these disruptions. It then develops a flexible agent-based model for examining supply chain disruption. The model facilitates examining many supply chain designs and parameters along with disruptions with varying characteristics.

## **1.3. Approach**

The model developed in this report is designed to allow for rapid alteration in the supply chain design, including the links between tiers and the number of establishments per tier. It also facilitates rapidly altering the characteristics of the establishments, including the inventory

times (i.e., material goods and finished goods) along with the frequency of shipments and other similar variables. The rapid altering of supply chain characteristics and establishment characteristics facilitates identifying generalizable trends that apply to many supply chains.

## 2. Supply Chain Resilience

The concept of supply chain resilience has gained significant attention in recent years due to the increasing frequency and severity of disruptions that can impact supply chains. Supply chain resilience (SCR) refers to the ability of a supply chain to withstand and recover from disruptions, such as natural disasters, supplier insolvency, or changes in demand. As Christopher and Peck noted, supply chain resilience is about the ability of a supply chain to cope with change, whether it is caused by disruption or by variability in demand or supply [6].

The literature on SCR is diverse; researchers have proposed several theoretical frameworks to understand supply chain resilience, including the resilience triangle framework, the supply chain resilience framework, and the dynamic capabilities framework. The resilience triangle framework, proposed by Sheffi and Rice, identifies three key elements of resilience: readiness, response, and recovery [7]. Readiness involves preparing for potential disruptions, response involves acting during a disruption, and recovery involves returning to normal operations after a disruption.

The development of SCR literature stems from a recognition that traditional supply chain risk management, often focused on known risks, was insufficient for systemic and unpredictable disruptions. Early conceptualizations highlighted agility, the ability to respond rapidly to unexpected changes, and robustness, the capacity to withstand disruptions without significant impact [6][9]. The supply chain resilience framework, developed by Pettit et al., identifies four key elements: robustness, agility, adaptability, and collaboration [8]. The current understanding of SCR incorporates the additional dimensions of visibility and redundancy:

- Robustness, referring to the ability of a supply chain to withstand disruptions;
- Agility, referring to the ability to respond quickly to changes;
- Adaptability, referring to the ability to adjust to new circumstances;
- Collaboration, referring to the ability to work with supply chain partners to share risk and coordinate responses, often involving working with supply chain partners to share risk and coordinate responses to disruptions, as highlighted by Simatupang and Sridharan [17];
- Visibility, which is the capacity to monitor product, information, and financial flows across the entire supply chain in real-time, where limited visibility or "supply chain opacity" represents a significant vulnerability [10];
- Redundancy, referring to strategic duplication of resources, such as multiple suppliers, alternative production facilities, or buffer inventories, to provide backup during disruptions [11];

Several other factors influence SCR at the meso- and macroscales, including supply chain flexibility, risk management, and supply chain complexity. Supply chain flexibility refers to the ability to adapt to changes in demand or supply, as discussed by Vokurka and O'Leary-Kelly [16]. Risk management involves identifying and mitigating potential risks, as emphasized by Kleindorfer and Saad [18]. Supply chain complexity refers to the level of complexity in the supply chain, including the number of nodes and links, as discussed by Choi and Krause [19].

To enhance SCR, organizations can implement various strategies, such as product and skill diversification, inventory management, supply chain visibility, collaboration, and business continuity planning. Diversification involves diversifying supply sources to reduce dependence on a single supplier, as suggested by Sheffi and Rice [7]. Inventory management involves maintaining strategic inventory buffers to absorb disruptions, as noted by Lee and Billington [20]. Supply chain visibility involves implementing technologies, such as RFID and GPS, to improve visibility, as discussed by Christopher and Lee [15]. There are several incentives for actors to engage in SCR, especially pre-emptively, as to be prepared for the eventuality of supply chain disruption. Empirical studies have shown that SCR is positively related to organizational performance, including profitability and customer satisfaction. For example, a study by Pettit et al. found that supply chain resilience was positively related to organizational performance [8]. Another study by Sheffi and Rice found that companies with more resilient supply chains were able to recover more quickly from disruptions [7].

Yet, there are limitations as to the reach and control a single firm or actor can influence within a complex supply chain. Collaboration involves building collaborative relationships with supply chain partners to share risk and coordinate responses, as highlighted by Simatupang and Sridharan [17]. Business continuity planning involves developing plans to ensure continuity of operations in the event of a disruption, as emphasized by Herbane et al. [21]. Recent studies have also explored the role of digital technologies in enhancing supply chain resilience. For instance, a study by Ivanov examined the impact of digital technologies on supply chain resilience and found that the use of digital technologies such as blockchain and artificial intelligence can improve supply chain resilience by enhancing visibility, agility, and adaptability [22].

The resilience of supply chains is directly linked to the broader concept of community resilience. A community's capacity to "prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions" [23] relies heavily on the functional integrity of supply chains delivering essential goods and services. These lifelines—including food, water, shelter, health and medical, energy, communications, transportation, and hazardous materials—are indispensable services that underpin human health, public safety, and economic security during and after a disaster.

Despite the increasing interest and advancements in supply chain resilience, several critical challenges and research gaps persist. A pervasive challenge is the absence of universally accepted metrics that can link and assist with collaboration across the supply chain and methodologies for accurately quantifying and assessing supply chain resilience, which limits comparative analysis, benchmarking, and the justification of resilience investments [10][24]. The dynamic nature of

global risks necessitates continued research to build robust and adaptive supply chains. Promising avenues for future inquiry include advanced predictive analytics, digital twin technology, interdependency modelling, incentive design and public-private collaboration, behavioural economics in supply chain resilience, research on the resilience of humanitarian supply chains, and measuring the community impact of SCR.

The pursuit of comprehensive supply chain disaster resilience remains an ongoing imperative and there are incentive misalignments in many cases between the origin of disruption and associated locations impacted by ripple effects [1][2]. The literature has significantly advanced the definition of supply chain resilience, identification of its key enablers, and effective strategies. However, persistent challenges, particularly in rigorous quantification and addressing the complexities of geographic and temporal aspects of supply chains, highlight the need for continued, collaborative research. Enhanced understanding of SCR and its direct connection to community resilience, robust and adaptive systems can better safeguard economic stability and societal well-being, across geographic and temporal scales.

### **3. Agent-Based Models and Related Analyses of Supply Chains**

The supply chain is a system that consists of material, information, and monetary flow between a variety of entities. The system begins with the acquisition of raw materials and moves downstream to the delivery of finished goods to the final consumers. Researchers and practitioners alike are continually trying to identify and manage all critical relationships within the supply chain on both an upstream and downstream level. Due to the high levels of complexity within these networks, it can be increasingly difficult to obtain information necessary to make production decisions. Information that is necessary for firms engaging in decision making typically resides across a high volume of resources. This information is everchanging and is generally presented in multiple forms.

Currently, most supply chain decision systems (e.g., tools and technologies), both in the industry and in research, are rather specific to a given enterprise and its supply chain. This means that the decision system cannot be easily modified to support and assist other enterprises and industries. Implementing agent-based modeling systems could help create a unified decision network to more efficiently translate information across a variety of enterprises and industries.

Recently, agent-based modeling has emerged as a technique to simulate complex interactions between varying entities within a supply chain. These entities span from manufacturers, distributors, retailers, and end consumers. This specific modeling structure allows for researchers and practitioners alike to analyze how disruptions or changes in behavior spread throughout the supply chain. More specifically, agent-based modeling can help determine the impacts of disruptions in the short-term downstream supply chain. By modeling each entity as an agent with its own decision-making rules and objectives, this approach more accurately reflects the dynamic nature of real-world supply chains.

Agent-based models provide an environment to understand how autonomous agents interact, adapt, and make decisions in dynamic environments. As investigated by Arvitrida, agent-based modeling systems present a number of opportunities to study supply chain networks in a new and innovative light [25]. They tend to model some aspects of real-world supply chains with increased accuracy since conventional models tend to treat supply chains as static systems. For example, if a manufacturer adjusts inventory strategies, or a supplier faces production constraints, an ABM simulation can reveal how these changes cascade throughout the network, affecting things such as delivery time, final inventory, and cost.

There is also currently a lack of real-time visibility into the entire supply chain, moving from raw materials to the end consumer, making it increasingly difficult to identify potential problems and respond quickly and efficiently to disruptions. Agent-based models could help mitigate these challenges as it simulates complex and dynamic scenarios in real time. These models can help identify how a supply chain may react to a disruption prior to a disruption occurring in the real world. Supply chain networks also currently face challenges in the areas of forecasting and planning. Accurately predicting demand and supply can be a challenging task, especially in

volatile markets, leading to inventory imbalances and reduced revenue. These challenges only grow when unexpected disruptions are introduced, such as natural disasters.

When evaluating agent-based models, it is necessary to understand the attributes that each individual agent possesses. Julka et al. claim that to be termed as an agent in a simulation, the discrete unit must have four main characteristics: autonomy, social ability, reactivity, and pro-activeness [28]. The agent must have some control over its actions and be able to work without human intervention while also containing the ability to communicate with other agents and/or human operators. It should also be able to react to changes in its environment while taking initiative on pre-specified goals. Although inventory is often a necessity, in a supply chain, typically each agent has both an incentive and objective to reduce its inventory, resulting in lower costs. This is done in part through optimizing the quantity to order. Although each agent is ultimately self-interested and has free will to decide when and how to respond to given information, typically the overall goal of the supply chain is to satisfy the end consumer. Without a common goal for all members of the supply chain, all agents will lose [26]. Aside from the individual agents themselves, it is also necessary to clarify and understand the components of a supply network. These networks typically consist of a collection of nodes (facilities) and their connecting arcs (transportation) [4]. Overall, agent-based modeling simulations allow researchers to mimic different scenarios and assess varying outcomes without needing to disrupt real-world supply chain operations. By simulating how autonomous agents interact, researchers and practitioners can identify emergent behavior, providing insights into overall supply chain dynamics.

### **3.1. Supply Chain Management**

One application for simulating supply chains using agent-based models is in efficient supply chain management. Supply chain management involves the coordination and optimization of materials, information, and finances across an entire supply chain. The process focuses on the movement of raw materials from production to distribution and finally to the end consumer. The literature suggests various strategies and decision systems for maintaining effective supply chain management, utilizing both agent-based modeling systems and insights from natural experiments. Fernandez et al. propose a service-orientated, agent-based monitoring subsystem designed to collect execution and environmental data, enabling more efficient assessment and detection of disruptive events [26]. The paper emphasizes enhancing management techniques to mitigate the impact of disruptive events on the supply chain.

Tang and Pan take an interesting approach to studying supply chain management by focusing on the bullwhip effect, a phenomenon where small fluctuations in demand lead to amplified variations in supply chain operations [27]. The authors employ an agent-based model to simulate different conditions and demand patterns, allowing them to analyze the impact of various factors on supply chain performance [27]. Their findings indicate that information sharing plays a critical role in reducing the bullwhip effect, which can lead to inefficiencies in supply chains. Furthermore, the study confirms that improved information sharing enhances

overall supply chain management, more so with networked supply chain systems where supply chain entities can have multiple upstream/downstream partners.

Julka et al. present an agent-based framework for analyzing supply chain dynamics and demonstrate the framework's application within a supply chain system [28]. Through simulation and subsequent analysis, the study aims to provide deeper insights into supply chain flows and the interactions between entities. By enhancing the understanding of these interactions and the movement of goods, the findings can be applied to improve supply chain management strategies and decision-making. Li and Chan expand on typical supply chain management literature and specifically consider the implementation of dynamic structures and how these structures potentially alter or improve issues present in supply chain management [29]. The authors develop an agent-based model to simulate both make-to-order and make-to-stock supply chains, incorporating dynamic structures to reflect real-world variability and complexity [29]. Other research on supply chain networks often uses methods other than agent-based models. For instance, Son et al. diverge from the agent-based modeling system and utilize a natural experiment approach in combination with supply network data to determine how firms' supply network structures changed after the 2011 Tohoku earthquake and tsunami in Japan [30]. The authors measure changes in the supply chain using degree centrality and ego network density [30]. Findings from the paper reveal that affected firms experience changes in their "supply network structures tending toward lower complexity."

Another application of agent-based modeling is demonstrated by Mizgier et al. who model disruption risks at the firm level to aid in identifying bottlenecks in a supply chain network [32]. Bottlenecks are slower points in the supply chain process where the flow of goods is restricted or takes a greater amount of time, which can disrupt and delay the entire supply chain. Mizgier et al. contribution to the literature is significant as they demonstrate how accurate bottleneck and disruption identification can support more efficient supply chain management decisions [32]. Li et al. build off of the literature presented by Mizgier et al. and consider the implications of disruptions on the supply chain management process [31]. Both Mizgier et al. [32] and Li et al. [31] summarize the significance of disruptions on supply chain management and offer constructive propositions for decision makers. Effective supply chain management is crucial for maintaining operational stability, minimizing disruptions, and ensuring the timely delivery of goods and services, ultimately contributing to overall business resilience and customer satisfaction.

As supply chains continue to grow and become more compactly interconnected, this increases the complexity of the systems themselves and their potential for failure. Cerca et al. conduct a systematic literature review on biorefineries, with a particular emphasis on bottlenecks from the strategic planning of new supply chains [33][32]. The authors conclude that there needs to be increased efforts for interdisciplinary and methodological diversity when it comes to the planning of supply chains to avoid significant bottlenecks. It is essential to include social sustainability into strategic decisions at the top of the supply chain to avoid bottlenecks downstream. On the other hand, Juttner compares varying measures of supply chain agent identification to identify bottlenecks in supply chain networks [34]. Results from the paper

indicate that a more accurate methodology for bottleneck identification needs to be developed and implemented across supply chain networks since the results are ambiguous [34]. This ambiguity could potentially be misleading for firms within supply chain networks, leading to poor supply chain management and substandard solutions for bottlenecks.

### **3.2. Resiliency in the Supply Chain**

Increases in globalization and collaboration between firms can result in supply chains advancing into supply chain networks [33]. This increase in supply chain dynamism and complexity can create an atmosphere where vulnerabilities are more prominent. By improving its resilience, a supply chain becomes more capable of withstanding disruptions, adapting to them effectively, and recovering rapidly. Due to the complex nature of supply chain networks, it can be increasingly difficult to build and maintain this resiliency. The following literature touches on resiliency in the supply chain and how agent-based models can be used to improve this resilience.

Van Voorn et al. use an agent-based model of a generic food supply chain to examine individual agent behavior and analyze the flow of goods between agents [35]. The authors explore potential strategies for enhancing resilience—the ability to withstand and recover from disruptions—while also considering the limitations and trade-offs related to improving overall efficiency [35]. Lu et al. also utilize an agent-based model but instead apply it to the case of Idaho’s potato supply chain [36]. Their model illustrates how shifts in consumer demand can lead to food waste and shortages. The findings reveal that the magnitude and timing of a demand shock affects various stakeholders in different ways [36]. By understanding the factors that drive changes both within and outside the supply chain, businesses and policymakers alike can develop strategies to enhance resilience and better manage disruptions.

Using a top-down approach to examine disruption-recovery dynamics, Tan develops a simulation model that combines a graph-based approach with an agent-based model of supply chain behaviors [33]. The results indicate that both mitigation and contingency strategies can enhance resilience by enabling faster recovery after disruptions. Tan finds that mitigation strategies are more effective for long-term disruptions, whereas contingency strategies are more effective for dealing with short-term disruptions. Overall, the paper leverages ABM to design a range of resilience strategies, including proactive mitigation strategies to strengthen the supply chain against disruptions and reactive contingency strategies to facilitate recovery.

Snyder et al. present a wide range of models for designing supply chains that are resilient to disruptions; with ABM being utilized in some of the models [37]. They stress that there is an abundance of model options available to planners to help them design resilient supply chain networks, however, the options are dependent on “the financial resources available, the decision maker’s risk preference, the type of network under consideration” and a variety of other market and individual factors [37]. Kim et al. also provide a valuable contribution to supply chain resilience literature but do so without the use of agent-based modeling. The authors conceptualize disruption and resilience within supply networks by examining the

structural relationships among entities in a supply network [4]. They determine that different relationships possess different levels of resilience and elaborate on how these results can be leveraged to increase resiliency in supply chain networks [4].

### **3.3. Supply Chain Disruption: Downstream and Upstream Losses**

Indirect supply chain losses often far exceed the losses of the direct damage caused by a disruption. For instance, Inoue and Todo estimate that the indirect effect of a lockdown on Tokyo (i.e., limitations on social interaction and business activity) would have twice the impact on other regions as it would have on Tokyo itself [39]. The same authors estimate that a major earthquake in Japan could cause an 11.1 % dip in the country's GDP with approximately 95 % of the losses being due to supply chain disruption [40]. A disruption in a network is seldom limited to local impacts [41].

The effects of a supply chain disruption can often be broken down into two major categories relating to point-of-loss: upstream and downstream. Upstream supply chain effects examine how suppliers of a disrupted firm are affected. On the other hand, downstream supply chain effects consider how customers of a disrupted manufacturer are affected. Supply chain studies can also be broken into two additional categories relating to scale: 1) micro economic studies that examine individual firms or limited scale supply chains and 2) macro studies that examine economy wide supply chains. Micro-scale studies, supported by a rich and diverse body of literature, offer valuable insights for manufacturers in managing their individual supply chains from their stakeholder perspective. On the other hand, macro scale supply chain studies provide insight for economy wide mitigation of supply chain disruption. At this scale, short-term downstream losses are among those that are less studied or are often excluded when estimating economic impacts, which introduces chronology of loss as another category. For instance, economic input-output analysis and computable general equilibrium (CGE) models, two primary approaches for estimating economy wide supply chain disruption losses, tend to exclude short-term downstream effects [1][2][3][42]. Economic input-output analysis tends to capture upstream effects while CGE models tend to estimate an equilibrium, which does not occur immediately following a disruption. A literature mapping from Thomas and Fung illustrate the lack of literature on short-term downstream impacts in regard to power disruption (see Table 3.1). Further, the annualized national losses for all supply chain disruptions are not well understood, as the frequency and severity of disruptions are not well documented. Correlation studies might capture total losses for a large-scale disruption but do not represent the annualized losses from all disruptions, which could be utilized in economic decision making for mitigating these disruptions.

Thomas and Fung attempt to address the gap in macro scale studies using a correlation study to estimate the impact of power disturbances on downstream value added [3]. This is done to examine the indirect impacts to downstream firms in the supply chains of four different industries ranging from manufacturing to the total private industry. The authors determine that power disturbances have a statistically significant effect on gross domestic product in the downstream supply chain such that the losses downstream exceed the direct losses [3]. Thomas

and Helgeson apply a similar model for examining natural and man-made hazards [1][2]. Because short-term downstream losses are more difficult to measure and track, agent-based modeling might shed light on them.

Information sharing throughout a supply chain can mitigate supply chain disruption, Ibrahim and Deghedi attempt to investigate the value of both downstream and upstream information sharing on alleviating disruption problems in the supply chain [38]. The authors evaluate an agent-based version of the Beer Game Model, a supply chain simulation game, to demonstrate how disruption, particularly those that occur directly within a firm, can negatively impact the overall performance of a supply chain. They also assess how sharing disruption information with other downstream agents can help block the development of risk in the supply chain and improve its overall performance [38].

**Table 3.1: Literature on Economic Impacts of Electricity Disruption by Time of Loss (long-term vs short-term) and Supply Chain Point (upstream vs downstream), from Thomas and Fung [3]**

		Supply Chain Point of Loss		
		Upstream	Direct	Downstream
Time of Loss	Short Term	<p>IDENTIFIED METHODS: CGE Models, Input-Output Models</p> <p>IDENTIFIED LITERATURE: Fried and Lagakos 2020; Rose et al 2005; Rose et al. 1997; Rose et al. 2007; Guha 2005; Wing and Rose 2018</p>	<p>IDENTIFIED METHODS: Direct loss, VoLL, production functions, econometric models</p> <p>IDENTIFIED LITERATURE: Castro et al. 2016; Linares and Rey 2013; Serra and Fierro 1997; Diboma and atieste 2013; Kim and Cho 2017; Oseni and Pollitt 2015; Woo et al. 2014; Linares and rey 2013; Castro et al. 2016; Wolf and Wenzel 2016; Zachariadis and Poullikas 2012; Moyo 2013; Adbasi 2018; Fisher-Vanden et al. 2015; Granger and Zhang 2019; Cole et al. 2018; ALam 2013; Alcott et al 2016; Abeberese et al. 2019; Coll-Mayor et al. 2012; Andersen and Dalgaard 2013; Das and McFarlane 2019; Niroomand and Jenkins 2020; Ozbafli and Jenkins 2016; Carlsson et al. 2011; Pepermans 2011; Abrate et al. 2016; Primen 2001; LaCommare and Eto (2006); Swaminathan and Sen (1997); Campbell (2012); President’s Council of Economic Advisers et al. (2013)</p>	★
	Long Term	<p>IDENTIFIED METHODS: CGE Models</p> <p>IDENTIFIED LITERATURE: Fried and Lagakos 2020; Rose et al 2005; Rose et al. 2007; Guha 2005; Wing and Rose 2018</p>	<p>IDENTIFIED METHODS: CGE models, econometric models, other forecasting models</p> <p>IDENTIFIED LITERATURE: Larsen et al 2018; Fried and Lagakos 2020; Andersen and Dalgaard 2013; Das and McFarlane 2019; Rose et al 2005; Rose et al. 1997; Rose et al. 2007; Guha 2005; Wing and Rose 2018</p>	<p>IDENTIFIED METHODS: CGE Models</p> <p>IDENTIFIED LITERATURE: Fried and lagakos 2020; Rose et al 2005; Rose et al. 2007; Guha 2005; Wing and Rose 2018</p>

NOTE: For the full citations, see Thomas and Fung cited above.

★ The topic area of Thomas and Fung

Aside from downstream movement, the literature also considers upstream processes within the supply chain. The upstream supply chain focuses on the supplier and encompasses where the products are created. It looks at the flow of materials, information, and resources from raw materials and through the supply chain. Gatti and Grugni place a particular focus on the trickle-down results of a disruption to upstream firms in the supply chain [43]. They employ an agent-based framework categorized by a credit network (connecting banks and firms) and a production network (connecting upstream and downstream firms) to investigate the macroeconomic and financial consequences of disruptions in the upstream supply chain [43]. They present the scenario of an epidemic erupting in the country where upstream firms are located. This introduces a dissemination of disruption, with upstream firms being temporarily shut down and downstream firms being unable to carry out production due to an interruption of the supply of intermediate inputs. The largest takeaway from the findings of Gatti and Grugni is the interconnectivity of the upstream and downstream aspects in supply networks. As demonstrated by the authors, “reduction of upstream supply forces downstream firms to cut back on production and sales. Therefore, downstream firms [will also] experience a contraction of profits and net worth.” The paper sheds light on the tradeoff between lean production and resilience in global value chains.

Julka et al. also touch on the parallels between upstream and downstream movement within the supply chain. The authors create a framework that considers the entire supply chain structure, attempting to identify and simulate all critical relationships, both upstream and downstream, within supply chains [28]. They propose a unified framework for modeling, monitoring, and managing to more accurately identify and quantify these relationships. This framework is then applied to a refinery supply chain. Julka et al. present an integrated approach for modeling and analysis of supply chains, which captures the interactions among enterprises and within the departments of an enterprise.

### **3.4. Supply Chain Disruptions and Mitigation**

Disruptions in the supply chain are unplanned events that interrupt the flow of goods, services, and information within a supply network. These disruptions can stem from various sources such as natural disasters, geopolitical conflicts, pandemics, cyberattacks, and logistical failures. In an increasingly interconnected global economy, even minor disruptions can have extensive consequences, leading to delays, increased costs, and supply shortages. It is necessary to understand the causes and impacts of supply chain disruptions to build models that can help enhance resilience and ensure stability in production and distribution networks. Scholars are increasingly recognizing the importance of understanding disruptions in supply chain networks. However, as stated by Kim et al., supply chain literature “still lacks a clear conceptualization of a network-level understanding of supply disruptions” [4]. The network nature of supply chains results in various emergent phenomena such as the bullwhip effect and inventory displacement, where reduction in inventory at one establishment increases risk and thereby inventory at other establishments [44]. This literature review presents a wide range of analysis methods utilizing agent-based models along with other experimental methods.

Rather than reacting to disruptions after the fact, several publications explore supply chains designed for resilience. If supply networks can be created to withstand disruptions and mitigate their impacts on the front end, this could help deter the dispersal of negative effects. Snyder et al. present a wide variety of models for designing supply chains that are resilient to disruptions [37]. The models are categorized by the status of the existing network, with each category being then divided by the underlying optimization model and risk measure. Findings from Snyder et al. illustrate a multitude of strategic planning models that are available for designing supply chain networks under the threat of disruptions [37].

Several papers investigate best practices in identifying and mitigating supply chain disruption-related risks through the implementation of agent-based models including Blos et al., Gatti and Grugni, and Chaturvedi et al. [42][45] [46]. Chaturvedi et al. present an agent-based simulation of a food supply chain for analysis and training against major disruptions. The paper demonstrates the effectiveness of using agent-based simulation to increase awareness and help educate companies and regulators about food defense risks and consequences of decision-making [46]. Gatti and Grugni employ agent-based models to examine the dissemination of disruption as it moves down the supply chain, looking at the macroeconomic and financial consequences of disruption[43]. Using agent-based modeling as a framework for simulations can be a valuable tool to effectively measure supply chain disruptions and run risk analysis for a high volume of firms across a variety of industries. This framework is further expanded upon by Nezami et al., Dulam et al. and Behdani et al. to facilitate a deeper understanding of the dissemination of disruption throughout the supply chain [47][48][49]. Nezami et al. focus on disruptions in the perishable goods supply chain concluding that price discounts play the most significant role in reducing the effects of specific disruptions on the supply chain [47]. Dulam et al. analyze the results of a large-scale natural disaster on a supply chain for manufacturing bottled water [48]. The paper details the effect that both panic buying and the consumer quota policy have on the supply chain after a disruption event occurs. Alternatively, Behdani et al. investigate a specific case of a lube oil supply chain through an ABM simulation-based risk analysis [49]. Their findings identify that the most efficient choice for managing supply disruptions is through implementing sourcing mitigation strategies [49]. The models and results presented in these reports can help evaluate management actions and assess damage caused by disruptions on the supply chain.

Both Tan and Rahman et al. focus heavily on the modeling of individual entities in the presence of disruptions [50][51]. Tan models a supply chain as a hierarchical network using agent-based modeling to model individual supply chain operations for each entity in a supply chain network [50]. Findings from the paper reveal that disruption mitigation strategies are more suitable for long-term disruptions whereas contingency strategies are more effective for short-term disruptions. Rahman et al. investigate a multi-echelon supply chain to quantify the economic impacts of extreme climate events along different stages of a potato supply chain in Idaho [51]. The authors run a simulation model employing ABM methods for five major types of agents within the supply chain. Findings reveal that the impacts of disruption events vary across agents and product categories. The models developed by both Tan and Rahman et al. can be applied to

other food and agricultural supply chains to better understand the vulnerabilities facing individual agents due to climate disruption events.

Generally speaking on the topic of supply chain disruptions, Ibrahim and Deghedi utilize an agent-based model of the Beer Game Model to demonstrate how disruptions, specifically those that occur in a supply chain, negatively affect the performance of the entire supply chain [38]. Findings from the paper show that sharing disruption information can help effectively block the dissemination of risk down the supply chain, while concurrently improving the overall performance of the supply chain. The results also stress that sharing information upstream in the supply chain has the potential to significantly alleviate problems erupting from disruptions. Li et al. investigate forward and backward disruption propagations (i.e., downstream and upstream) and the resulting ripple effect that places stress on the supply chain network [31]. The authors use an agent-based model to delineate supply chain disruption behavior. The findings indicate that forward disruption propagation can be generally mitigated by substitute and backup supply. This type of disruption has a greater effect on firms in supply networks and those that serve the assembly role. Juttner outlines an agent-based model and compares varying measures of supply chain agent identification procedures to calculate loss distribution of production disruptions in manufacturing networks [34]. The author quantifies the effects of different model specifications and varying risk factors on expected losses and other measures of risk.

Aside from agent-based modeling methods, several papers in this area of literature implement other experimental methods to quantify and analyze the presence of disruption in supply chains and their networks. A number of papers examine the structural relationships among individual entities within the supply chain network [25]. This is done to efficiently conceptualize supply network disruptions and improve resiliency, as demonstrated by Son et al. who use a natural experiment approach to measure disruptions from the 2011 Tohoku earthquake and tsunami in Japan [30]. Bimpikis et al. develop an equilibrium characterization model to study multitier supply chain networks in the existence of disruption risk [52]. The authors determine that suppliers and retailers typically possess misaligned incentives regarding best practices for the structure of the supply chain [52]. This can create management complications, particularly when it comes to how to handle disruptions in the supply network.

Platitas and Ocampo consider supply chain disruptions as they relate to inflation in global supply chains across the Philippines and other East Asian economies [53]. The authors do not use agent-based modeling but rather utilize a local projection approach to explore the inflationary impact of disruptions. Results from the report show that disruption events do result in statistically significant increases in inflation across the majority of Asian economies investigated with a “considerable impact on the tradeable segment of core inflation” [53].

The literature presented in this section can help better understand the financial impact of network disasters and disruptions. Regardless of the model used to analyze disruptions in supply chains, it is essential to understand how said disruptions affect the relationships between individual entities and the supply chain as a whole.

### 3.5. Gaps

As discussed previously, supply chain disruption losses can be classified by scale (micro vs macro), point-of-loss (upstream vs downstream), and chronology (short-term vs long-term), as illustrated in Figure 3.1. Much of the current literature focuses on specific problem areas within the supply chain, such as inventory management, distribution systems, and discrepancies in consumer demand. These studies often do not consider the supply chain as a complete structure or consider how major disruptions create trickle down, upstream/downstream problems within the supply chain itself. Further, there is a lack of clear conceptualization regarding disruptions at a network level [4]. By neglecting to understand supply disruptions at this level can prevent stakeholders from fully mitigating the negative effects of a supply disruption. This suggests that there is a partial gap on macro issues, as illustrated in the right-hand yellow shading of Figure 3.1. There is another partial literature gap in that there is not sufficient data to estimate macro level annualized losses (e.g., national losses due to disruption). Many macro loss assessments are for large individual events, such as a hurricane. Macro studies that examine losses due to supply chain disruption also tend to exclude short-term downstream losses due to the difficulty in measuring and tracking them, leaving the upper right corner of Figure 3.1 with an additional literature gap (shaded red).

There is currently a research gap in the resiliency area of supply chains. Several authors effectively determine the outcomes of disruptions on the supply chain after they occur, whether this is reduced demand, decreased profits, or bottlenecking; however, more is needed to evaluate the overall resiliency of supply networks. Agent-based modeling can be used to

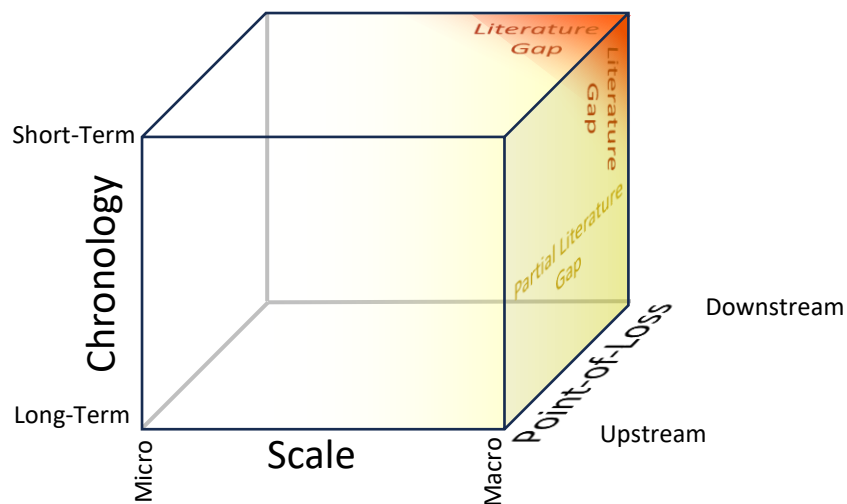


Figure 3.1: Illustration of Loss Classification and Literature Gaps

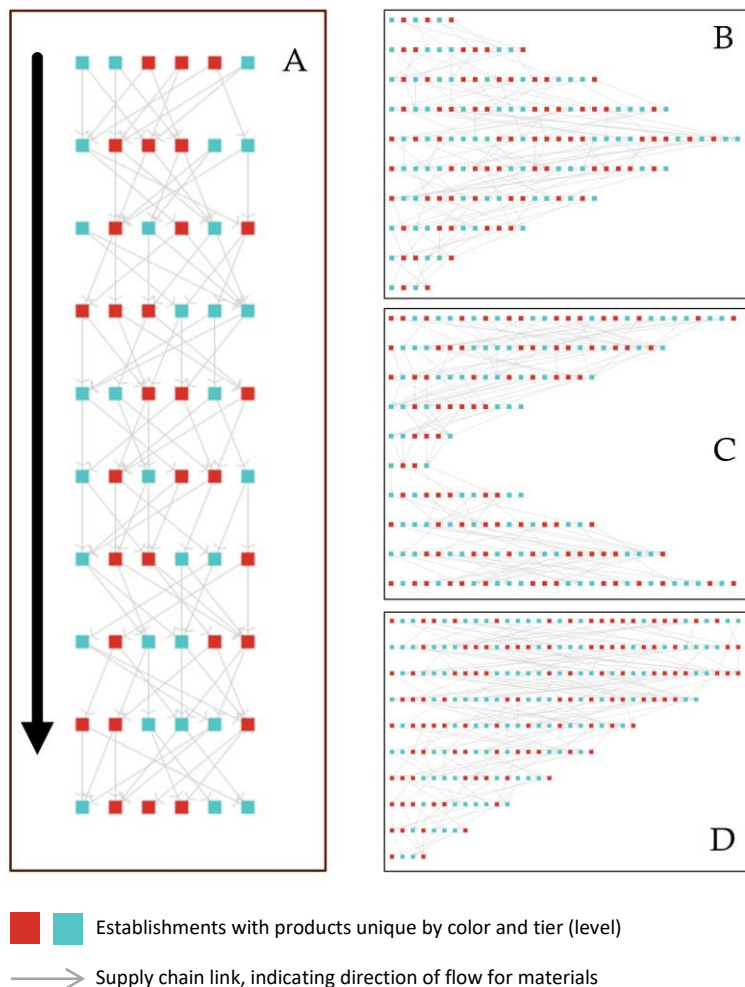
simulate disruptions (e.g. natural disasters, strikes, and cyber-attacks) and assess how well the supply chain can withstand them. This supply chain resiliency gap also extends to crisis management. Other needs include examining alternatives for recovery from major disruptions. Agent-based modelling can provide insights into how different actors in the supply chain will react during a crisis, allowing for better planning and coordination.

## 4. Modeling Supply Chains

In order to better understand the losses that result from supply chain disruption and to identify relevant emergent behavior, an agent-based model was developed that allows for examining the various types of supply chains that might exist. For instance, those that diverge (i.e. have very few establishments upstream and many establishments downstream) or converge (i.e., have many establishments upstream and few establishments downstream). Further, it allows for there to be products that are sole sourced or have few establishments that have substitutable products. This model can have prices implemented into it, but for its initial design it focuses on the flow time through the establishments and the supply chain.

### 4.1. An Agent-Based Model

The agent-based model was developed in NetLogo to simulate supply chain activity for a 10-tier or less supply chain. In supply chains, the term “tier” is often used to refer to suppliers and numbered by their position relative to a particular establishment/consumer; thus, a tier 1 supplier directly supplies to a manufacturer while a tier 2 supplier provides suppliers the tier 1 supplier. The model allows the number of establishments to fluctuate for each simulation. Each tier can be divided into as many as 6 groups with each group making a different product. The simulation runs in steps of 1-hour increments for a number of hours determined by the user. Connections from one tier to another are determined randomly at the beginning of each iteration of the simulation where each establishment randomly connects with a user



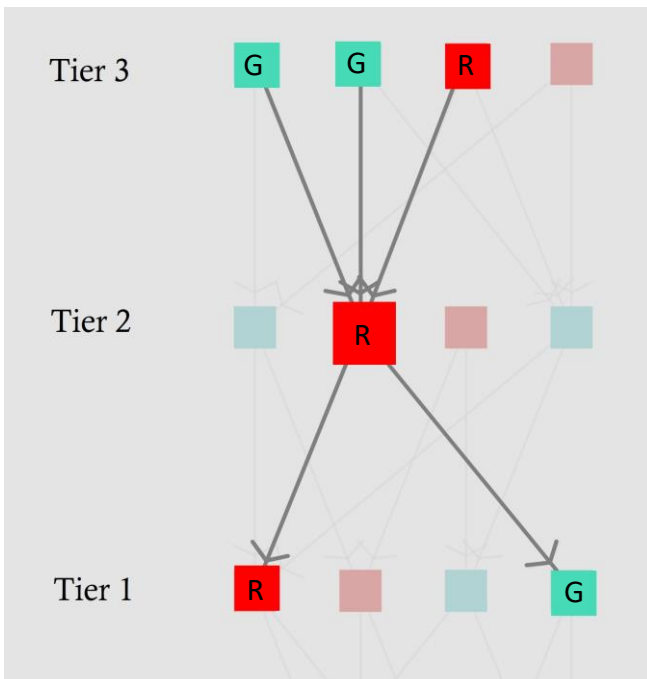
NOTE: Four supply chains are shown, each boxed and labeled with a letter for reference. Materials flow downward as indicated by the black arrow.

**Figure 4.1: Example Supply Chains for Agent-Based Model**

defined number of establishments in the next downstream tier. The connections from a particular establishment to customer establishments in the next tier can be a set number or randomly selected from either a uniform distribution, normal distribution, Poisson distribution, or exponential distribution as determined at the onset of the simulation.

Four examples of supply chain models are provided in Figure 4.1, labeled A, B, C, and D. Each square represents an establishment, and each row represents a supply chain tier with goods flowing from the top to the bottom. There are links between each tier representing the relationship between suppliers and customers. As illustrated, each supply chain can have a different number of establishments in each tier. For these examples, each tier produces two products, identified by different colors.

Baseline or typical production for a particular establishment is set to use one unit of input from each supplier (determined by the connections) to produce one unit of output per customer per hour. For instance, consider the example in Figure 4.2 that has two *Tier 3* green suppliers (see the top row) and one *Tier 3* red supplier for one red *Tier 2* establishment (see the middle row), which supplies two *Tier 1* customers (see the bottom row). Note that an establishment's products are unique by tier and by color; thus, two red establishments in the same tier have substitutable products while two red establishments in different tiers do not have substitutable products. The *Tier 2* establishment (see the middle row) needs two green units and one red unit



NOTE: Green establishments are noted with "G" while red establishments are noted with an "R."

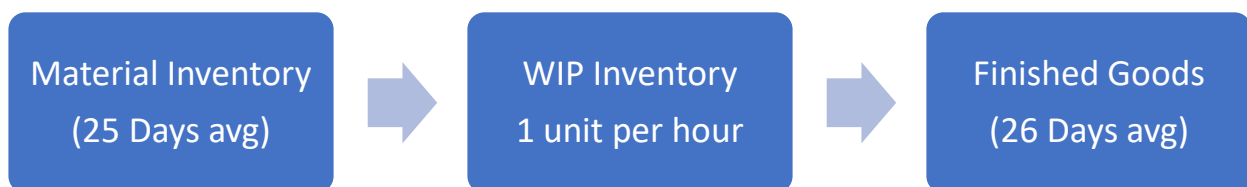
**Figure 4.2 Example of Inputs and Outputs for Agent-Based Model**

from *Tier 3* (see the top row), determined by the links to its suppliers. These units are needed to produce two units of red *Tier 2* output (one for a red *Tier 1* customer and one for a *Tier 1* green customer), determined by the links created to customers. For the baseline, each hour the red *Tier 2* establishment will produce two units that all together require three units of input; however, as discussed below the rate of production can be altered to meet demand or if inventories start to build up. If a supplier is short on a product, an establishment can purchase goods from another supplier of the same type (i.e., color) only if they already have an existing connection; thus, no new connections can be created while the simulation is running. Thus, if one of the green suppliers in *Tier 3* from Figure 4.2 is short on supplies, the *Tier 2* establishment can get more green units from the other green *Tier 3* supplier; however, if both green suppliers in *Tier 3*

have no inventory, the *Tier 2* establishment cannot get green supplies. Production levels are determined based on factors specific to each establishment, as described below.

The model makes assumptions in that the establishments are price takers and there is perfectly inelastic demand, which aids in identifying any phenomena, thresholds, or tendencies that occur as a result of network effects. It is also important to note that this is a system of make-to-stock as opposed to make-to-order, where establishments maintain some level of inventory rather than producing product after orders are received. However, inventory times can be reduced such that it resembles make-to-order.

Each establishment has material inventory, work-in-progress inventory, and finished goods inventory, as illustrated in Figure 4.3. The maximum level of inventory for materials and finished goods are selected at the beginning of a simulation. It can be set the same for all establishments or each establishments maximum can be selected from a normal distribution with the average and standard deviation indicated at the beginning of each simulation. The inventory is measured in days of supplies at the baseline production. Appropriate levels of inventory were determined using methods described in the next section. Transportation or transfer time is assumed to be incorporated into the material inventory time and the finished goods inventory time. Figure 4.4 illustrates the establishment processes as a part of the supply chain simulation. Production is varied by the level of finished goods inventories. If inventories are at or below 20 %, the production target is 100 % of the establishment capacity. Production targets decrease by 1.25 percentage points for every 1.00 percentage point increase in inventories; thus at 100 % inventory the production target is 0 % of capacity. This approach follows a “base stock policy” where the establishment is bringing finished goods inventory up to a predetermined level (i.e., base stock level) with 20 % of that level being a threshold for max production to avoid a shortage. As inventory approaches the base stock level production is scaled back. As inventory is depleted production is increased. To avoid abrupt starts and stops in production, the target rate of production is proportionally adjusted based on inventory levels. Each establishment’s new target takes a randomly selected amount of time to reach. The time is selected randomly from between 48 and 96 hours with the amount of time varying each cycle. At baseline, establishments produce 1 unit per customer per hour and only ship full orders. The size of each order is determined at the beginning of the simulation from a random selection of one of five options: 6, 8, 12, 24, and 48.



NOTE: Each establishment’s inventory time is selected from a normal distribution with the average indicated in the boxes.

**Figure 4.3 Illustration of the Processes within an Establishment**

Establishments can increase production by a maximum level determined at the initial setup of each simulation. For instance, if the level is set at 20 %, then the firm can increase its production by a maximum of 20 % from its baseline, which is determined by the number of customers it has. For instance, if an establishment has 5 customers and can increase production by a maximum of 25 %, then its baseline is 5 units of production per hour, and it can increase that rate to 6.25 per hour. The maximum increase can be a set value for all establishments or selected from a normal distribution for each establishment where the average and standard deviation for the distribution is selected at the beginning of the simulation. Establishments ship to customers when there is demand and availability and on a first come first serve basis, which is randomly determined; that is, the order in which customers “purchase” goods during a particular 1-hour step is randomly selected. The maximum material inventory for each establishment is selected at the beginning of each simulation either as a set number or from a normal distribution where the average and standard deviation is selected.

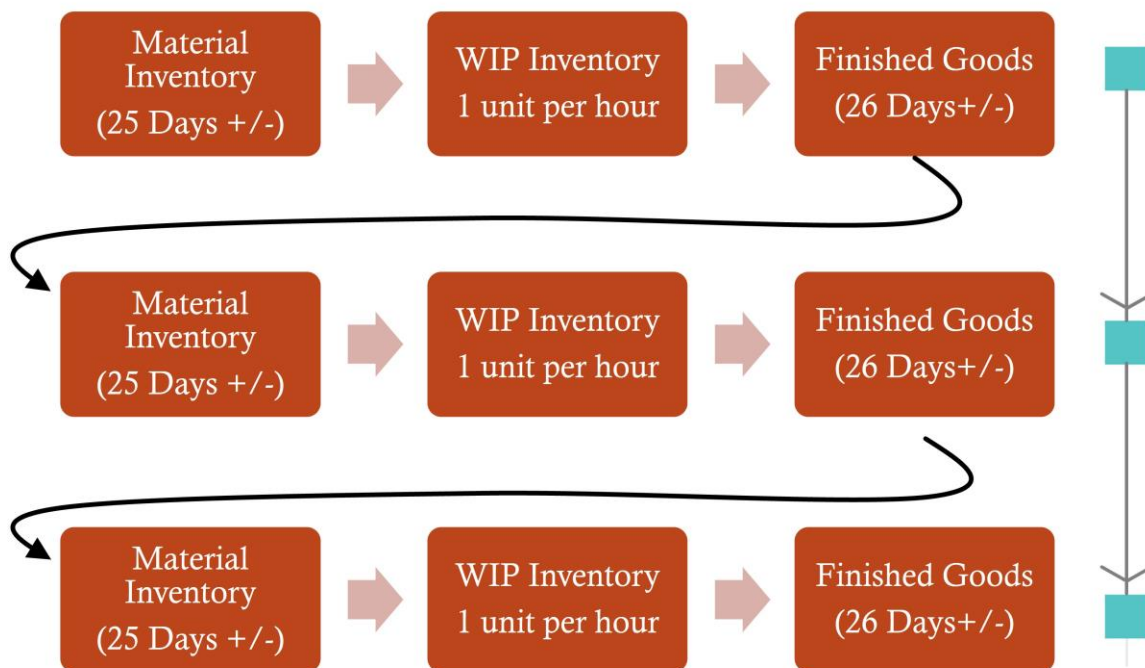


Figure 4.4 Illustration of a Supply Chain Simulation

It is important to note that there are some limitations in the types of networks that result from the approach used in the modeling discussed above, which can be addressed with alterations to the model if needed. The model does not allow connections that bypass a tier. For instance,

there are no connections between tier 9 and tier 7 except through tier 8. It is not clear to what extent this affects the outcomes from a simulation. Kim et al. note that certain types of supply chain networks fare better during a disruption, particularly those where the relationships follow a power-law that often looks like a hub and spoke and is sometimes referred to as scale-free [4]. This makes sense, as an establishment that experiences a disruption is likely to have fewer connections.

#### 4.2. Estimating Model Inventory Times

There is a wide range of possibilities for selecting inventory times in the model. Appropriate times were selected based on data from the U.S. manufacturing industry. The method used for calculating industry flow time does not track the flow of physical goods directly, but rather tracks the monetary flow, which parallels the flow of physical goods [54]. This paper uses the term “flow time,” but can also be referred to as throughput time, which is the time that elapses between buying raw materials for the production process and selling the finished product [55]. As discussed below, Thomas lays out examining flow time at the industry and supply chain level [56].

The calculation for flow time can be thought of as water flowing through a pipe into a container. The cost of goods sold, *COGS*, is the total amount of water that runs into the container over a period of time and the inventory values are the amount of water in the pipe at any given time. Since the total amount of water that flowed out of the pipe (i.e., the amount in the container or *COGS*) is a known value, we can estimate how many times the pipe was filled and emptied over that period of time (inventory turns or *TRN*) by dividing the amount in the container by the volume of the pipe. If one takes the number of days in a year and divides it by the number of inventory turns *TRN*, the result is the flow time *FT*, which represents the time it takes to move from the beginning to the end of the pipe. This method makes the assumption of first-in first-out (FIFO) where the oldest goods on hand are sold first [54]. This paper breaks the industry inventory time into three categories: material goods, work-in-process, and finished goods. The method for estimating the average flow time for materials and supplies to move through material inventory, work-in-process inventory, and finished goods inventory for a particular industry, represented by NAICS codes, is the following:

$$FT_{IND,i} = \frac{(INV_{IND,i,BOY} + INV_{IND,i,Eoy})/2}{(INV_{IND,Total,BOY} + INV_{IND,Total,Eoy})/2} \times \frac{365}{TRN_{IND,Total}} \quad (1)$$

where

$FT_{IND,i}$  = Flow time for industry *IND* and inventory type *i*, where *i* is materials and supplies (MS), work-in-process (WIP), or finished goods (FG) inventories  
*i* = Inventory item where *i* is materials and supplies (MS), work-in-process (WIP), or finished goods (FG) inventories.

$INV_{IND,Total,BOY}$  = Total inventory (i.e., materials and supplies, work-in-process, and finished

goods inventories) for industry *IND* at the beginning of the year (BOY)  
 $INV_{IND,Total,EOY}$  = Total inventory (i.e., materials and supplies, work-in-process, and finished goods inventories) for industry *IND* at the end of the year (EOY)  
 $TRN_{IND,Total}$  = Inventory turns for industry *IND* (defined below)

This equation calculates, for any industry, the flow time for materials and supplies inventories, work-in-process inventories, and finished goods. The sum of flow time *FT* for each of the three flow times is the average total flow time for an industry. The days that a dollar spends in each of the inventory categories is being calculated by taking the total number of days in a year and dividing it by the number of inventory turns *TRN*, which is discussed below. This is then multiplied by average inventory of type *i* divided by the total inventory.

Inventory turns,  $TRN_{Total}$ , is the number of times inventory is sold or used in a time period such as a year [55][57][58]. It is calculated as the cost of goods sold (COGS), which is the cost of the inventory that businesses sell to customers [55], divided by the average inventory:

$$TRN_{IND,Total} = \frac{COGS_{IND}}{\left(\frac{INV_{IND,Total,BOY} + INV_{IND,Total,EOY}}{2}\right)} \quad (2)$$

where

$$COGS = AP + FB + MAT + DEP + RP + OTH + (INV_{Total,BOY} - INV_{Total,EOY})$$

*AP* = Annual payroll

*FB* = Fringe benefits

*MAT* = Total cost of materials

*DEP* = Depreciation

*RP* = Rental payments

*OTH* = Total other expenses

Inventory turns is usually stated in yearly terms and is used to study a number of fields, such as distributive trade, particularly with respect to wholesaling [58]. The data for calculating *COGS* is obtained from the Annual Survey of Manufacturing. In the previous two equations, inventories are calculated by taking the average of the beginning of year inventories and end of year inventories for a particular industry, which is considered a standard practice [55]. It is important to note that the work-in-process time inherently includes downtime when the factory is closed.

### 4.3. Simulation Example

A set of simulations was run with the parameters shown in Table 4.1 to illustrate model results. Each simulation had ten tiers each having 50 establishments with 20 customers per establishment for tiers 1 through 9. Note that the last tier does not have customers, as previously discussed. As previously mentioned, establishments can increase production by an amount determined at the initial setup of each simulation. For each establishment this value is

selected from a normal distribution with a mean of 33 % and relative standard deviation of 16.7 %. The mean and standard deviation were selected based on the utilization rate of the manufacturing industry shown in the Quarterly Survey of Plant Capacity Utilization for quarter 4 of 2020 [59], the year for which the flow time is calculated. The maximum material inventory for each establishment is selected at the beginning of each simulation from a normal distribution with a mean of 25 days’ worth and a relative standard deviation of 15 %. The mean was selected based on calculating the industry average material inventory flow time for 2020 using methods discussed in Section 4.2 and from NIST Technical Note 1890 [60]. A set of 1000 simulations were run with each being 3000 hours long (125 days or nearly 18 weeks). Note that the average amount of finished goods inventory for the U.S. manufacturing industry is 28 days’ worth, is calculated using methods in NIST Technical Note 1890 [60], and uses data from the 2020 Annual Survey of Manufactures [61]. This estimate was used in the model with a 15 % standard deviation. There is an initial model setup that includes 2000 cycles or hours to bring the model to a stable point. Inventory is initially set at 50 % of the maximum inventory less a random number between 1 and the total units per shipment for that establishment.

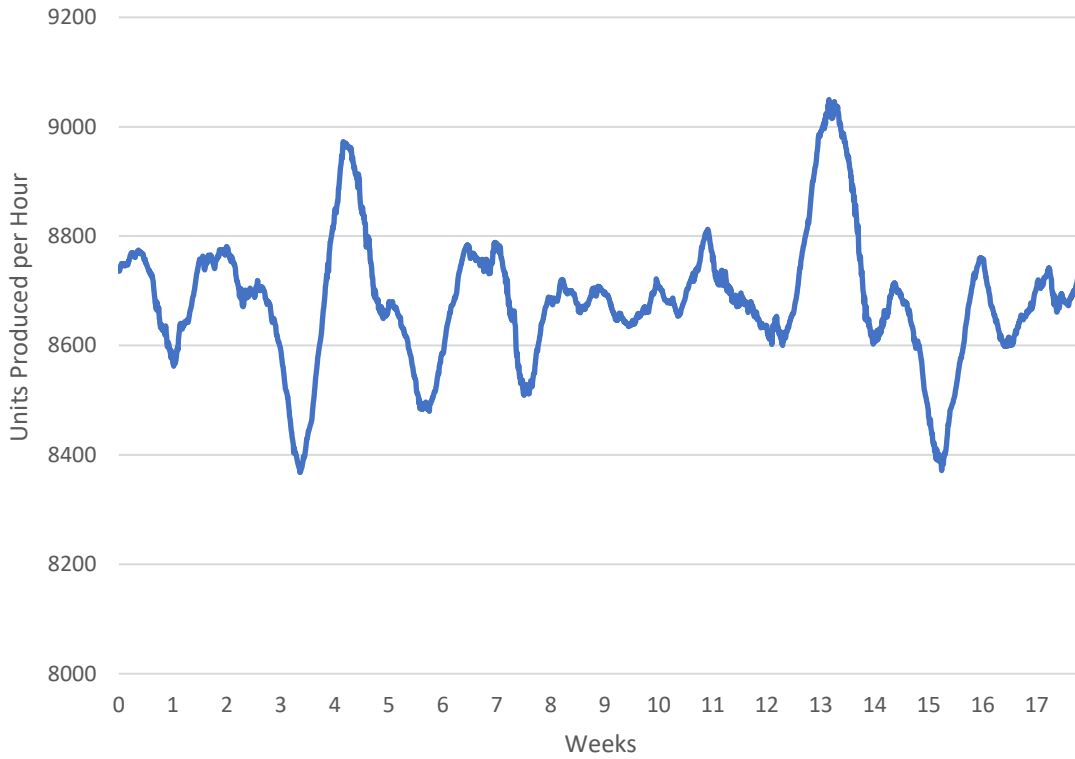
**Table 4.1: Parameters for Example Simulation**

	Number or Average	Distribution
Tiers	10	n/a
Establishments per Tier	50	n/a
Max production	133 % of baseline	Normal with 16.7 % st. dev.
Material inventory	25 days	Normal with 15% st. dev.
Finished goods inventory	28 days	Normal with 15% st. dev.

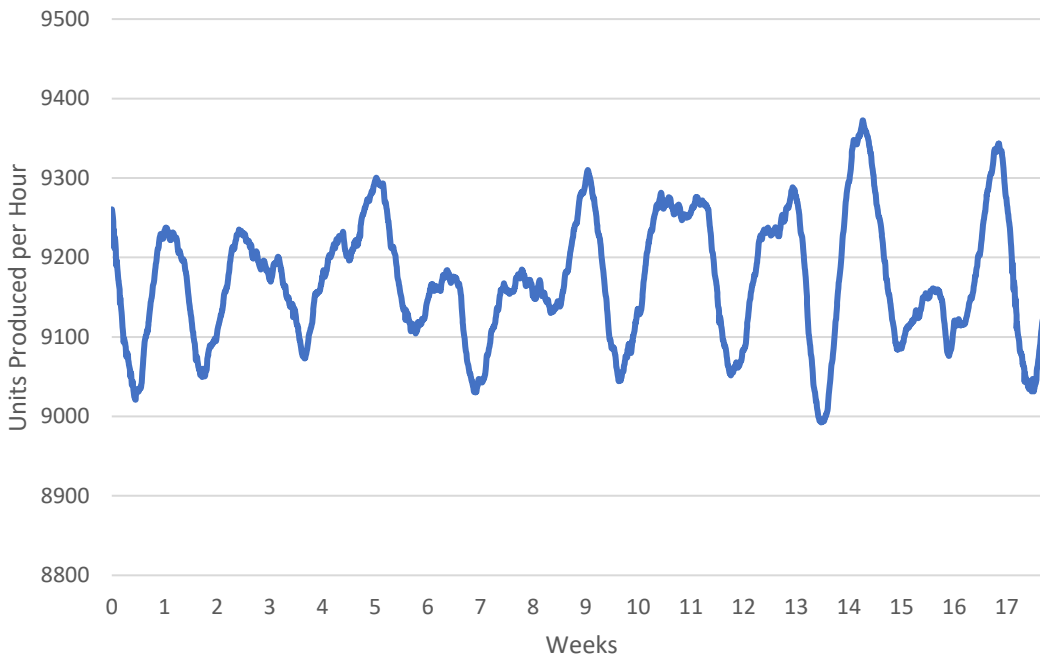
n/a Not Applicable

st. dev. Standard Deviation

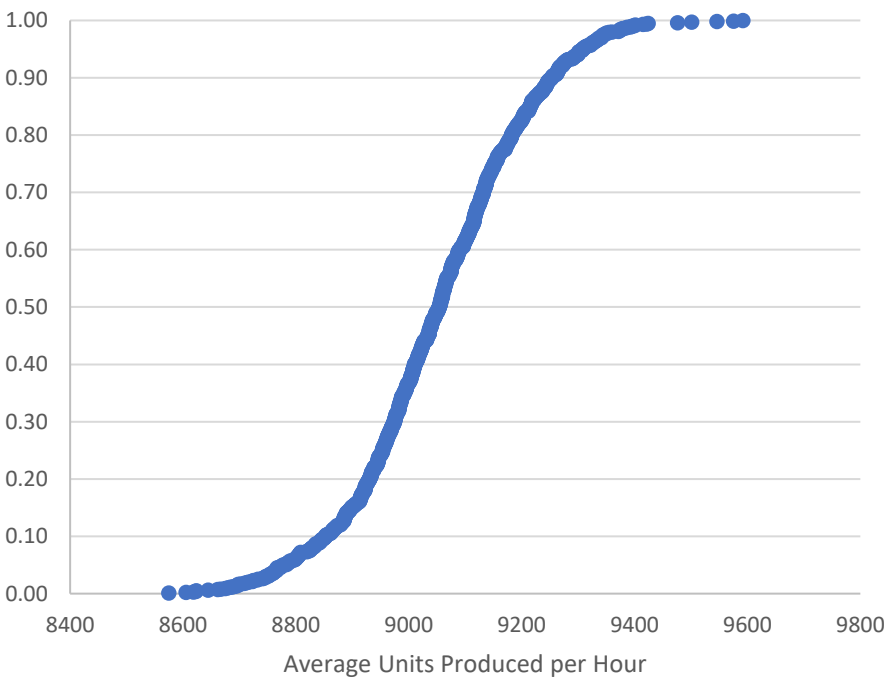
Figure 4.5 and Figure 4.6 each graph the units produced per hour for an example simulation with both examples run using the parameters discussed above. One can see that the units produced oscillates; thus, the results suggest that the unit production for an aggregated supply chain might oscillate naturally due to their basic nature, as this model is void of variability in final demand, seasonal effects, or other factors that might drive fluctuations. This oscillation is potentially due to using inventory, a lagging indicator, to determine production levels. Although the oscillation appears large in the figures, they are actually fairly low. For instance, in Figure 4.5 the per hour production only increases to 4.2 % above the average and 3.6 % below. For Figure 4.6, it decreases by 1.9 % and increases by 2.2 %. Future models might incorporate varying methods for determining production levels, such as increased communication between establishments. Figure 4.7 graphs the average units produced per hour for all 1000 simulations. The median value is 9054.0 with a low of 8574.7 and a high of 9591.8.



**Figure 4.5: Example Simulation 1: Units Produced per Hour**



**Figure 4.6: Example Simulation 2: Units Produced per Hour**



**Figure 4.7: Cumulative Probability Graph of the Average Unit Production per Hour, 1000 Simulations**

#### 4.4. Application

Presented above was a flexible agent-based model where various aspects of the model can fluctuate, including the number of tiers, establishment per tier, products per tier, flow time, substitutability, and potentially other aspects. This flexibility allows for examining four aspects of supply chains:

- Disruption
- Network level analysis
- Establishment characteristics/behavior
- Short-term downstream losses

The flexibility allows for the exploration of diverse supply chain structures resulting in the ability to examine disruption in the context of a network-level analysis—addressing a gap identified in the existing literature (see Section 3.5 and Figure 3.1). The model further facilitates examining other establishment characteristics (e.g., inventory levels and ordering decisions) to understand how those factors interact with network design. Finally, the model can simulate short-term losses that occur downstream resulting from disruptions, a subject area that has limited coverage in the literature (see Section 3.5 and Figure 3.1). The ability to investigate these four aspects simultaneously can uncover previously unobserved emergent phenomena or provide deeper insight into known phenomena.

## 5. Summary

Agent-based models and other analyses have been used to examine and simulate supply chains to gain insight into supply chain management, resiliency, and disruption. This report broke the literature into four subject areas:

- Supply chain management
- Resiliency in the supply chain
- Supply chain disruption: downstream and upstream
- Supply chain disruptions and mitigation

A great deal of the research on these topics focuses on enhancing the decisions of individual firms that order goods, as this includes one of the clearer stakeholders; however, the inherent nature of supply chains is that one entity can affect other entities through their linkages, making it critical to understand the larger scale phenomena.

Supply chain disruption losses themselves can be classified by scale (micro vs macro), chronology (short-term vs long-term), and point-of-loss (upstream vs downstream). There is a literature gap relating to macro short-term downstream losses; that is, there is limited understanding of the aggregated losses that occur when goods fail to arrive at the next point in the supply chain. There is also a limited understanding of the frequency and magnitude of supply chain disruptions that makes it difficult to estimate annualized losses, which are useful for guiding investment in mitigation. Further, there is a literature gap in understanding supply chains from a network-level perspective. Manufacturers tend to respond from their stakeholder position in the supply chain; however, this natural process can result in an underinvestment in mitigation/prevention of supply chain disruption.

Research in the literature has uncovered tendencies or phenomena such as the bullwhip effect or inventory displacement, where maintaining lower inventory for one point in the supply chain pushes another point to increase inventory. Understanding supply chain phenomena in the aggregate is less well understood. Given the challenge of data on supply chains, agent-based models provide an opportunity for better understanding potential supply chain behaviors. This report presents a flexible agent-based model that allows various aspects of the model to fluctuate, including the number of tiers, establishment per tier, products per tier, flow time, substitutability, and potentially other aspects. This flexibility allows for the exploration of diverse supply chain structures and supports network-based analysis—addressing a gap identified in the existing literature. The model further facilitates examining other establishment characteristics (e.g., inventory level) to understand how they interact with network design. Analyses using this model can uncover previously unobserved emergent phenomena or provide deeper insight into known ones. The results using this model might also be able to provide insights into the magnitude of short-term, downstream, macro-level losses by providing insight into the propagation of losses/disruptions. The model was demonstrated using a series of 1000 simulations run to provide a proof-of-concept. It was observed that production oscillates, likely as a result of production being determined by inventory.

## References

- [1] Thomas, Douglas; Helgeson, Jennifer. (2021). "The effect of natural/human-made hazards on business establishments and their supply chains." *International Journal of Disaster Risk Reduction*. 59(1). June 2021. <https://doi.org/10.1016/j.ijdrr.2021.102257>
- [2] Thomas, Douglas; Helgeson, Jennifer. (2022). "The Effect of Natural Hazard Damage on Manufacturing Value Added and the Impact of Spatiotemporal Data Variations on the Results." *International Journal of Disaster Risk Science*. Vol 13: 691-704. <https://doi.org/10.1007/s13753-022-00438-x>
- [3] Thomas D, Fung J (2022) Measuring downstream supply chain losses due to power disturbances. *Energy Economics* 114:106314. <https://doi.org/10.1016/j.eneco.2022.106314>
- [4] Kim Y, Chen Y, Linderman K (2015) Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management* 33–34(1):43–59. <https://doi.org/10.1016/j.jom.2014.10.006>
- [5] Macal, C. and North, M. (2010) Tutorial on Agent-Based Modelling and Simulation. *Journal of Simulation*, 4, 151-162. <https://doi.org/10.1057/jos.2010.3>
- [6] Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management*, 15(2), 1-14.
- [7] Sheffi, Y., & Rice, J. B. (2005). A supply chain view of the resilient enterprise. *MIT Sloan Management Review*, 47(1), 41-48.
- [8] Pettit, T. J., Fiksel, J., & Croxton, K. L. (2010). Ensuring supply chain resilience: Development of a conceptual framework. *Journal of Business Logistics*, 31(1), 1-21.
- [9] Manyena, S. B. (2006). The concept of resilience revisited. *Disasters*, 30(4), 433-450.
- [10] RAND. (2023). Supply chain resilience: Challenges and opportunities. Retrieved from <https://www.rand.org>
- [11] Sheffi, Y. (2005). *The resilient enterprise: Overcoming vulnerability for competitive advantage*. MIT Press.
- [12] Tukamuhabwa, B. R., et al. (2015). Supply chain resilience: A review and directions for future research. *Journal of Supply Chain Management*, 51(3), 1-18.
- [13] Modi, S. (2024). Inter-organizational relationships and supply chain resilience. *Journal of Supply Chain Management*, 50(1), 1-15.
- [14] Ketokivi, M., et al. (2017). Collaborative supply chain management: A review and directions for future research. *Journal of Supply Chain Management*, 53(1), 1-16.
- [15] Christopher, M., & Lee, H. L. (2004). Mitigating supply chain risk through improved confidence. *International Journal of Physical Distribution & Logistics Management*, 34(5), 388-396.
- [16] Vokurka, R. J., & O'Leary-Kelly, S. W. (2000). A review of empirical research on manufacturing flexibility. *Journal of Operations Management*, 18(4), 485-501.
- [17] Simatupang, T. M., & Sridharan, R. (2002). The collaborative supply chain. *International Journal of Logistics Management*, 13(1), 15-30.
- [18] Kleindorfer, P. R., & Saad, G. H. (2005). Managing disruption risks in supply chains. *Production and Operations Management*, 14(1), 53-68.

- [19] Choi, T. Y., & Krause, D. R. (2006). The supply base and its complexity: Implications for transaction costs, risks, responsiveness, and innovation. *Journal of Operations Management*, 24(5), 637-652.
- [20] Lee, H. L., & Billington, C. (1992). Material requirements planning and supplier management. *Journal of Operations Management*, 11(2), 147-159.
- [21] Herbane, B., Elliott, D., & Swartz, E. (2004). Business continuity management: Time for a strategic role? *Long Range Planning*, 37(5), 435-457.
- [22] Ivanov, D. (2022). Digital supply chain management: a review and directions for future research. *International Journal of Production Research*, 60(2), 531-546.
- [23] McAllister, T. P., et al. (2015). Community resilience: A review of the literature and a framework for understanding and enhancing community resilience. *Journal of Homeland Security and Emergency Management*, 12(2), 259-283.
- [24] Serbetcioglu, G., & Oflac, B. S. (2025). Measuring supply chain resilience: A review and directions for future research. *Journal of Supply Chain Management*, 51(2), 1-15.
- [25] Arvitrida NI (2018) A review of agent-based modeling approach in the supply chain collaboration context. *IOP Conference Series: Materials Science and Engineering* 337:012015. <https://doi.org/10.1088/1757-899X/337/1/012015>
- [26] Fernández E, Toledo CM, Galli MR, Salomone E, Chiotti O (2015) Agent-based monitoring service for management of disruptive events in supply chains. *Computers in Industry* 70:89–101. <https://doi.org/10.1016/j.compind.2015.01.009>
- [27] Tang Z, Pan Y (2014) Agent-based supply chain management modeling and simulation. 2014 IEEE International Conference on Information and Automation (ICIA) (IEEE, Hailar, Hulun Buir, China), pp 1255–1259. <https://doi.org/10.1109/ICInfA.2014.6932841>
- [28] Julka N, Srinivasan R, Karimi I (2002) Agent-based supply chain management—1: framework. *Computers & Chemical Engineering* 26(12):1755–1769. [https://doi.org/10.1016/S0098-1354\(02\)00150-3](https://doi.org/10.1016/S0098-1354(02)00150-3)
- [29] Li J, Chan FTS (2013) An agent-based model of supply chains with dynamic structures. *Applied Mathematical Modelling* 37(7):5403–5413. <https://doi.org/10.1016/j.apm.2012.10.054>
- [30] Son B-G, Chae S, Kocabasoglu-Hillmer C (2021) Catastrophic supply chain disruptions and supply network changes: a study of the 2011 Japanese earthquake. *International Journal of Operations & Production Management* 41(6):781–804. <https://doi.org/10.1108/IJOPM-09-2020-0614>
- [31] Li Y, Chen K, Collignon S, Ivanov D (2021) Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability. *European Journal of Operational Research* 291(3):1117–1131. <https://doi.org/10.1016/j.ejor.2020.09.053>
- [32] Mizgier KJ, Jüttner MP, Wagner SM (2013) Bottleneck identification in supply chain networks. *International Journal of Production Research* 51(5):1477–1490. <https://doi.org/10.1080/00207543.2012.695878>
- [33] Cerca M, Sosa A, Gusciute E, Murphy F (2022) Strategic planning of bio-based supply chains: Unlocking bottlenecks and incorporating social sustainability into biorefinery systems. *Sustainable Production and Consumption* 34:219–232. <https://doi.org/10.1016/j.spc.2022.09.013>

- [34] Jüttner MP (2012) Systemic relevance in financial markets and manufacturing networks. (University of Zurich). <https://doi.org/10.5167/UZH-164195>
- [35] Van Voorn G, Hengeveld G, Verhagen J (2020) An agent-based model representation to assess resilience and efficiency of food supply chains. *PLOS ONE* 15(11):e0242323. <https://doi.org/10.1371/journal.pone.0242323>
- [36] Lu L, Nguyen R, Rahman MM, Winfree J (2021) Demand Shocks and Supply Chain Resilience: An Agent-Based Modelling Approach and Application to the Potato Supply Chain. (National Bureau of Economic Research, Cambridge, MA), w29166, p w29166. <https://doi.org/10.3386/w29166>
- [37] Snyder LV, Scaparra MP, Daskin MS, Church RL (2022) Planning for Disruptions in Supply Chain Networks. <https://doi.org/10.1287/educ.1063.0025>
- [38] Ibrahim Y, Deghedi G (2012) Sharing Breakdown Information in Supply Chain Systems: An Agent-Based Modelling Approach. 2.
- [39] Inoue, Hiroyasu; Todo, Yasuyuki. (2020). "The propagation of economic impacts through supply chains: The case of a mega-city lockdown to prevent the spread of COVID-19." *PLoS ONE* 15(9). <https://doi.org/10.1371/journal.pone.0239251>
- [40] Inoue, Hiroyasu; Todo, Yasuyuki. (2019). "Firm-level propagation of shocks through supply-chain networks." *Nature Sustainability* 2, 841–847 (2019). <https://doi.org/10.1038/s41893-019-0351-x>
- [41] Bahdani, Bahzad; Dam, Koen H. van; Lukszo, Zofia. (2011). "Agent-based modeling for disruption management in industrial networks and supply chains." 2011 International Conference on Networking, Sensing and Control, Delft, Netherlands, 2011, pp. 157-162. IEEE <https://doi.org/10.1109/ICNSC.2011.5874947>
- [42] Nealy, Michael. (2023). Assumptions of I-O. IMPLAN. <https://support.implan.com/hc/en-us/articles/18944187743643-Assumptions-of-I-O>
- [43] Gatti DD, Grugni E (2021) Breaking Bad: Supply Chain Disruptions in a Streamlined Agent-Based Model.
- [44] Calhoun, Steven. (2021). "Don't Ditch the Lean Supply Chain." <https://www.veryableops.com/blog/dont-ditch-lean-supply-chain>
- [45] Blos MF, Da Silva RM, Miyagi PE (2015) Application of an Agent-based Supply Chain to Mitigate Supply Chain Disruptions. *IFAC-PapersOnLine* 48(3):640–645. <https://doi.org/10.1016/j.ifacol.2015.06.154>
- [46] Chaturvedi A, Armstrong B, Chaturvedi R (2014) Securing the food supply chain: understanding complex interdependence through agent-based simulation. *Health and Technology* 4(2):159–169. <https://doi.org/10.1007/s12553-014-0086-7>
- [47] Nezami MN, Eshlaghy AT, Iranban S-J (2023) Design an agent-based model of the supply chain of perishable goods in the conditions of specific disruptions.
- [48] Dulam R, Furuta K, Kanno T (2020) Development of an agent-based model for the analysis of the effect of consumer panic buying on supply chain disruption due to a disaster. *Journal of Advanced Simulation in Science and Engineering* 7(1):102–116. <https://doi.org/10.15748/jasse.7.102>
- [49] Behdani B, Adhitya A, Lukszo Z, Srinivasan R (2012) Mitigating Supply Disruption for a Global Chemical Supply Chain-Application of Agent-based Modeling. *Computer Aided*

- Chemical Engineering (Elsevier), Vol. 31, pp 1070–1074. <https://doi.org/10.1016/B978-0-444-59506-5.50045-6>
- [50] Tan WJ (2020) Modelling and simulation of supply chain resilience using complex system approaches. (Nanyang Technological University). <https://doi.org/10.32657/10356/137144>
- [51] Rahman MM, Nguyen R, Lu L (2022) Multi-level impacts of climate change and supply disruption events on a potato supply chain: An agent-based modeling approach. *Agricultural Systems* 201:103469. <https://doi.org/10.1016/j.agsy.2022.103469>
- [52] Bimpikis K, Candogan O, Ehsani S (2019) Supply Disruptions and Optimal Network Structures.
- [53] Platitas RJC, Ocampo JCG (2024) From bottlenecks to inflation: Impact of global supply-chain disruptions on inflation in select Asian economies. *Latin American Journal of Central Banking*:100141. <https://doi.org/10.1016/j.latcb.2024.100141>
- [54] Meigs, R.F. and W.B. Meigs. (1993) *Accounting: The Basis for Business Decisions*. 9th edition. New York, McGraw-Hill Inc.
- [55] Horngren, C.T., W.T. Harrison Jr. and L.S. Bamber (2002) *Accounting*. 5th edition. Upper Saddle River, NJ, Prentice Hall.
- [56] Thomas, Douglas. (2018) "An examination of national supply-chain flow time." *Economic Systems Research*. Vol 30 issue 3, 359-379. <https://doi.org/10.1080/09535314.2017.1407296>
- [57] Stickney, C.P. and P.R. Brown (1999) *Financial Reporting and Statement Analysis*. Mason, OH, Southwestern, 136-137.
- [58] Hopp, W.J. and M.L. Spearman (2008) *Factory Physics*. 3rd edition. Long Grove, IL, Waveland Press.
- [59] U.S. Census. (2025). Quarterly Survey of Plant Capacity Utilization. <https://www.census.gov/programs-surveys/qpc.html>
- [60] Thomas, Douglas S. and Kandaswamy, Anand M. (2015) Inventory and Flow Time in the US Manufacturing Industry. NIST Technical Note 1890. <http://dx.doi.org/10.6028/NIST.TN.1890>
- [61] U.S. Census Bureau. (2025). Annual Survey of Manufactures. <https://www.census.gov/programs-surveys/asm.html>
- [62] Chaturvedi A, Armstrong B, Chaturvedi R (2014) Securing the food supply chain: understanding complex interdependence through agent-based simulation. *Health and Technology* 4(2):159–169. <https://doi.org/10.1007/s12553-014-0086-7>
- [63] Ibrahim Y, Deghedi G (2012) Sharing Breakdown Information in Supply Chain Systems: An Agent-Based Modelling Approach. 2.
- [64] Kim Y, Chen Y, Linderman K (2015) Supply network disruption and resilience: A network structural perspective. *Journal of Operations Management* 33–34(1):43–59. <https://doi.org/10.1016/j.jom.2014.10.006>
- [65] Lau JSK, Huang GQ, Mak KL, Liang L (2006) Agent-based modeling of supply chains for distributed scheduling. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 36(5):847–861. <https://doi.org/10.1109/TSMCA.2005.854231>
- [66] Li Y, Chen K, Collignon S, Ivanov D (2021) Ripple effect in the supply chain network: Forward and backward disruption propagation, network health and firm vulnerability.

- European Journal of Operational Research 291(3):1117–1131.  
<https://doi.org/10.1016/j.ejor.2020.09.053>
- [67] Long Q, Zhang W (2014) An integrated framework for agent-based inventory–production–transportation modeling and distributed simulation of supply chains. *Information Sciences* 277:567–581. <https://doi.org/10.1016/j.ins.2014.02.147>
- [68] Lu L, Nguyen R, Rahman MM, Winfree J (2021) Demand Shocks and Supply Chain Resilience: An Agent-Based Modelling Approach and Application to the Potato Supply Chain. (National Bureau of Economic Research, Cambridge, MA), w29166, p w29166. <https://doi.org/10.3386/w29166>
- [69] Snyder LV, Scaparra MP, Daskin MS, Church RL (2022) Planning for Disruptions in Supply Chain Networks. <https://doi.org/10.1287/483ca90f-76d7-48ca-8808-7e85d4b7b688>
- [70] Son B-G, Chae S, Kocabasoglu-Hillmer C (2021) Catastrophic supply chain disruptions and supply network changes: a study of the 2011 Japanese earthquake. *International Journal of Operations & Production Management* 41(6):781–804. <https://doi.org/10.1108/IJOPM-09-2020-0614>
- [71] Tan WJ (2020) Modelling and simulation of supply chain resilience using complex system approaches. (Nanyang Technological University). <https://doi.org/10.32657/10356/137144>
- [72] Urciuoli L (2016) Paper Title: ABM-Based Supply Chain Risk Analysis and Modelling.

## Appendix A. Agent-Based Modeling Publications

Table A. 1: Publications on Agent-Based Modeling and Supply Chains

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Arvitrida (2018) [25]</b>	Supply chain collaboration, considering strategic partnerships between companies along the supply chain	No focus on disruption	Yes	Literature review based on journal articles that apply ABM in supply chain collaboration	Provides insights to researchers about the opportunities ABM presents in studying supply chain collaboration
<b>Behdani et al. (2012) [49]</b>	Supply chain disruptions and how to mitigate	Significant focus on disruption	Yes	The authors present a “simulation-based risk analysis approach using an agent-based model and its application for a specific case of a lube oil supply chain.”	Findings show that the sourcing mitigation strategy (production plants source from two suppliers, one low cost and one back up) is the most efficient choice for managing supplier disruptions in most scenarios
<b>Bimpikis et al. (2019) [52]</b>	Supply chain disruptions	Medium focus on disruption	No	The authors develop an equilibrium characterization model to study multitier supply chain networks in the existence of disruption risk  The main objective of the paper is to derive insights “into the way network structure affects the output, prices, and expected profits of firms in the supply chain.”	The results of the paper yield that firms’ profits may vary nonmonotonically in the reliability of production in different tiers.  Results determine that suppliers’ and retailers’ incentives on the structure of the supply chain are typically misaligned which can create management problems.

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Blos et al. (2015) [45]</b>	Supply chain disruptions and how to mitigate	High focus on disruption	Yes	<p>The authors explore how to identify and mitigate supply chain disruption-related risks through the implementation of an agent-based model.</p> <p>The ABM forms the framework on which to run risk analysis on.</p>	<p>Disruption scenarios are generated, and an ABM is used to evaluate management actions and assess damage on the supply chain.</p> <p>This approach is used as a tool to deal with supply chain disruptions in manufacturing firms</p>
<b>Cerca et al. (2022) [33]</b>	<p>Bottlenecking</p> <p>Strategic planning in supply chains</p>	No focus on disruption	No	The report employs a systemic literature review on biorefineries, bottlenecks from strategic planning of new supply chains, and social sustainability in supply chains	<p>Findings from the paper expose the need for interdisciplinary efforts and methodological diversity in biorefinery supply chain planning.</p> <p>Results show the negative impacts of bottlenecks and highlight the importance of incorporating social sustainability into strategic decisions at the top of the supply chain</p>
<b>Chaturvedi et al. (2014) [62]</b>	Supply chain disruptions	Significant focus on disruptions	Yes	<p>Paper presents an agent-based simulation of the food supply chain for analysis and training against major disruptions</p> <p>“The Food Defense Simulation is based on the Reference World Information and Simulation Environment platform. RWISE platform provides an agent-based modeling environment that faithfully mimics the dynamics of the real world.”</p>	<p>The paper demonstrates the effectiveness of using ABM to increase awareness for companies and regulators about food defense risks and consequences</p> <p>The research provides a basis for integrating human-in-the-loop decision makers with automated models of decision makers.</p>

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Dulam et al. (2020) [48]</b>	Supply chain disruptions	Significant focus on disruption	Yes	The authors implement an agent-based modeling architecture to analyze the results of a large-scale natural disaster on a bottled water supply chain	Results detail the effect of panic buying and the consumer quota policy on the supply chain after a disruption event. The authors believe that their model can be expanded to understand the financial impact of disruptions
<b>Fernandez et al. (2015) [26]</b>	Schedules of supply chains Supply chain management	Significant focus on improving management of disruptive events impact on the supply chain	Yes	A service-orientated, agent-based monitoring subsystem is proposed. The system uses a reference model for defining monitoring models and collects execution and environment data to assess and detect disruptive events	Uses ABM to address supply chain monitoring by structuring monitoring subsystem functionalities as a set of autonomous entities
<b>Gatti and Grugni (2021) [42]</b>	Supply chain disruptions Particular focus on the trickle-down results of a disruption to upstream firms	Significant focus on disruption Distribution of disruption throughout the supply chain	Yes	The authors investigate the macroeconomic and financial consequences of two types of disruptions (full and partial contraction) in the supply chain using an ABM. Identified by a credit network and a production network.	Report indicates that when the likelihood of a disruptive event is high, managers and researchers alike should place a strong emphasis on resilience and optimization of the production network

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Ibrahim and Deghedi (2012) [63]</b>	Downstream and upstream supply chain movement  Supply chain disruptions  Information sharing in the supply chain	Medium focus on disruptions	Yes	The authors utilize an agent-based model of the Beer Game Model to demonstrate how disruptions negatively affect the performance of the entire supply chain The concept of reverse information sharing (supply-side information) is also introduced as a mechanism for sharing breakdown information.	Findings show that sharing factory disruption information can help block the evolution of risk downstream the supply chain, while improving the overall performance of the supply chain  RIS has the potential to significantly alleviate a factory disruption problem
<b>Julka et al. (2002) [28]</b>	Supply chain management  Economy wide supply chains  Touches on downstream and upstream movement within the supply chain	Looks at disruptions specific to decision support systems in supply chains, particularly due to the fact that these systems tend to be specific to individual enterprises	Yes	Section 1 highlights a framework for analysis and Section 2 demonstrates the application of the framework to a refinery supply chain	The report presents “the supply chain and its related problems through a unified, flexible, and scalable framework” to better understand supply chain flows and entities

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Juttner (2012) [34]</b>	Supply chain disruptions Bottlenecking  Downstream and upstream supply chain movement	Significant focus on disruption	To some extent	Dissertation consisting of four research papers (papers three and four are of relevance)  Model is proposed to calculate loss distribution of production disruptions in manufacturing networks. Bottlenecks are identified in the supply chain.	The authors quantify the effects of different model specifications and varying risk factors on expected losses and other measures of risk. The paper heeds ambiguous results which could potentially be misleading for supply chain management
<b>Kim et al. (2015) [64]</b>	Supply chain resiliency  Supply chain disruptions	Significant focus on disruptions	No	The authors compare four varying supply network structures to more effectively understand supply network disruption and resilience.	Findings reveal that disruptions at the node/arc level do not necessarily lead to network-level disruptions.  Results indicate the importance for planners to differentiate a node/arc disruption versus a network disruption
<b>Lau et al. (2006) [65]</b>	Economy wide manufacturing supply chains	No focus on disruption	Yes	The authors model a supply chain as a multiagent system while considering a distributed scheduling problem  They conduct a literature review, a mathematical formulation of the scheduling problem, and an agent-based model of the supply chain	Results show that modified contract-net protocol (MCNP) outperforms CNP, and performs comparably with centralized heuristic (CTR) when project complexity is high in terms of the total supply chain operating cost

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Li and Chan (2013) [29]</b>	Dynamic structures in supply chains  Outlines attributes and actions of individual agents in the supply chain	No focus on disruption	Yes	The authors build an agent-based model to simulate “make-to-order” and “make-to-stock” supply chains with dynamic structures over three experiments	The authors build a common agent-based model for MTO and MTSSO supply chains that can be expanded into other application domains for future research
<b>Li et al. (2021) [66]</b>	Upstream and downstream supply chain  Supply chain disruptions	Medium focus on disruption	Yes	Looks at forward and backward disruption propagations and the resulting ripple effects  An ABM is used to delineate supply chain disruption behavior, and an analysis is conducted on both types of propagations.	Results indicate that forward disruption propagation can generally be mitigated by substitute and backup supply. Backward disruption propagation is mitigated by flexible operation and distribution.
<b>Long and Zhang (2014) [67]</b>	Integrated supply chains and their features/layers  Entire supply chain network	No focus on disruption	Yes	The paper proposes an “integrated framework for agent-based inventory-production-transportation modeling and distributed simulation” in complex supply chains	The authors build on the conceptual agent model and build a computation agent model that can be implemented into a multi-agent system  This model can help reduce the complexity and difficulty of building simulation models, in turn reducing costs and shortening turnover cycles
<b>Lu et al. (2021) [68]</b>	Supply chain Resilience	Significant focus on disruption	Yes	The authors develop an ABM based on the case of Idaho’s potato supply chain. Model demonstrates “why food waste and shortages may occur with shifts in consumer demand.”	Findings show that both magnitude and timing of the demand shock have different impacts on a variety of stakeholders in the supply chain

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Mizgier et al. (2013) [32]</b>	Supply chain risk management  Bottlenecking	Significant focus on disruption	No	The authors “model disruption risks (measuring frequency and severity) on the firm level using renewal-reward processes.”	Measures for bottleneck identification are summarized  The authors believe that combining their proposed method with pre-existing measures will achieve precise bottleneck identification in order to support supply chain risk management decisions
<b>Nezami et al. (2023) [47]</b>	Supply chain for perishable goods  Supply chain disruptions	Medium focus on disruption	Yes	The authors design an agent-based model for the perishable goods supply chain during the occurrence of specific disruptions (model is built using NetLogo software)	According to the findings, discounts played the most significant role in reducing effects of specific disruptions on the supply chain
<b>Platitas and Ocampo (2024) [53]</b>	Supply chain disruptions and their impacts specifically on inflation  Bottlenecking	Medium focus on disruption  Measures supply chain losses due to mismatches in supply and demand for goods and services	No	The authors utilize a local projection approach to explore the inflationary impact of global supply chain disruptions in Philippines and other East Asian economies	Findings show that disruption events result in statistically significant increases in inflation across investigated Asian economies. Non-tradable inflation tends to have a short-lived and insignificant response to global supply chain pressures.

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Rahman et al. (2022) [51]</b>	Supply chain disruptions	Significant focus on disruption	Yes	The report uses a multi-echelon supply chain simulation model using ABM to quantify a variety of economic impacts of different extreme climate events along different stages of a potato supply chain in Idaho.	Findings show that the impacts of disruption events vary across agents and product categories  The price hike for fresh potatoes is significantly higher than processed potatoes during disruption events.
<b>Snyder et al. (2022) [69]</b>	Supply chain disruptions  Planning for disruptions within supply chain networks  Supply chain resilience	Significant focus on disruption	Yes	The authors present a variety of models for designing supply chains that are resilient to disruptions.  The models are categorized by the status of the existing network. Each category is then divided by the underlying optimization model and the risk measure.	The findings illustrate a multitude of strategic planning models “available for designing supply chain networks under the threat of disruptions.”  The authors emphasize that a planner’s choice of model depends on several factors such as network type, status of existing facilities, the firm’s risk preference, and resources available
<b>Son et al. (2021) [70]</b>	Supply chain disruptions  Supply chain management	Significant focus on disruption	No	The authors use a natural experiment approach and supply network data from Factset to inquire how supply chain structures were altered after the 2011 Tohoku earthquake and tsunami in Japan. This is measured using degree centrality and ego network density	Findings show that compared to unaffected firms, affected firms experience changes in their “supply network structures tending toward lower complexity measured by in-degree centrality, out-degree centrality and ego network density.”

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Tan (2020) [50]</b>	Supply chain resilience  Supply chain disruptions	Medium focus on disruption	Yes	A top-down approach is used to design SCN topologies. A bottom-up approach using ABM is used to evaluate the operational performance of the SCN topologies.  Trade-offs between mitigation and contingency strategies and backorder cost and ordering cost are analyzed	Findings show that mitigation strategies are more suitable for long-term disruptions whereas contingency strategies are more effective for short-term disruptions
<b>Tang and Pan (2014) [27]</b>	Supply chain management	No focus on disruption  The report highlights the bullwhip effect under different demand patterns and supply chain structure	Yes	An agent-based system is used to model the supply chain  A simulation is conducted under four varying sets of conditions	The report finds that information sharing can reduce the bullwhip effect. The benefit of information sharing is also confirmed in the context of network supply chains

References	Aspect of the supply chain discussed	Extent that supply chain disruption is discussed	Is agent-based modeling implemented in analysis	Methods/nature of study	Main findings
<b>Thomas and Fung (2022) [3]</b>	Supply chain disruptions Downstream supply chain	Significant focus on disruption, specifically the impact of power disturbances across varying industries	No	Rather than using a modeling method, the authors measure observations of value added before and after power disturbances to examine the indirect impacts at downstream firms in the supply chains of four different manufacturing industries.	Power disturbances have a statistically significant effect on gross domestic product (i.e. value added),” particularly in the manufacturing industry. There was a 0.8% to 3.3% increase in value added in the absence of disturbances based on the given industry.
<b>Urciuoli (2016) [72]</b>	Supply chain risk analysis	Minimal focus on disruption	Yes	The paper applies ABM to “facilitate the quantification of the impacts of security risks and related countermeasures.”	The methodology may provide insights into the reduction of security threats, potential to jam postal systems, delays experienced by customers.
<b>Van Voorn et al. (2020) [35]</b>	Resiliency and efficiency of food supply chains	Medium focus on disruption  Authors consider one type of disruption per simulation	Yes	The report employs an agent-based model of a generic food supply chain to investigate the flow between agents and explore agent behavior	Findings show that network structures with higher efficiency tend to be more sensitive to shocks, where less efficient network types are more resilient.