A NETWORK TOPOLOGY APPROACH FOR OBSERVING THE IMPACT OF EXTERNAL DISRUPTIONS ON MASS PERSONALIZATION SUPPLY CHAIN NETWORKS

by

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(Under the Direction of Beshoy Morkos)

ABSTRACT

Mass personalization (MPP) is a novel production method that integrates the consumer into the design process, efficiently producing distinct, scalable products that satisfy intangible consumer needs. Previous MPP research has focused on the Industry 4.0 manufacturing processes and technologies required to make personalization a feasible method. Inherently, MPP necessitates a configurable supply chain that accommodates fluctuating product requirements. However, there has been little effort to examine the resilience and robustness of MPP supply chain networks in instances of external disruptions. This research develops network topologies for three interviewed MPP firms and determines the impact of external factors such as the COVID-19 pandemic. The study finds that MPP firms have varying network topologies, flexible supplier networks, and direct-to-consumer/business distribution. Faced with disruption, firms with specialty, centralized suppliers were vulnerable, while firms with increased supplier redundancy, transitivity, and visibility were robust and resilient.

INDEX WORDS: Mass personalization, Industry 4.0, Supply chain networks, Resilience, Robustness

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DEDICATION

This work is dedicated to the dynamic life and memory of Keaton Coker.

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CHAPTER 1

INTRODUCTION

This research examines the supply chain network (SCN) structure of the mass personalization production (MPP) paradigm and its subsequent impact on a firm's resilience and robustness. Product personalization is defined as the process of delivering customized goods derived from consumer desires. Personalization allows companies to gain a competitive advantage by expanding the product design space and realizing once intangible consumer experiences. However, technology, cost, and infrastructure have limited fully personalized products, yet incremental industrial advancements have narrowed the gap between creating cost-effective, mass-produced products and capturing latent consumer requirements. The most recent progression, Industry 4.0 (I4.0), revolutionizes both the manufacturing and supply chain space with flexible, connected production systems such that mass personalized product variations are becoming a reality.

Contrasting mass customization (MC), which provides consumers with limited post-design choices, MPP allows pre-design input from consumers, adding value through unique, differentiating products. For instance, consider a workbench with a set number of modular add-ons versus one designed to the exact design specifications of the consumer. However, this input alters the structure and design of the product's components and requires advanced manufacturing techniques and a highly integrated SCN to guarantee low final product cost and short lead times, differentiating the method from craft production. Consequently, the successful implementation of MPP relies on understanding the increasingly interconnected global SCN structure, which consists of several hundred enterprises, including suppliers (tier 1, 2, 3), manufacturers, distributors, and retailers.

To manage supply chain design complexity and overcome the proprietary nature of SCN data, supply chain researchers use an interdisciplinary field of study known as network theory to computationally conceptualize an approximate SCN model by assigning each firm as a node connected by relational links (Choi & Wu, 2009). This proxy model forms a connected topography that permits a deeper understanding of competitive advantage through the diffusion of information, social control of opportunism, and coordination & aid (Borgatti & Li, 2009). Additionally, researchers can utilize network models to simulate disruptions over an extended time horizon, such as the recent COVID-19 outbreak, to highlight an SCN's vulnerabilities and mitigate risk diffusion.

Previous research has shown three network topologies that best describe realistic SCNs - random, small-world, and scale-free (Strogatz, 2001; Nair & Vidal, 2011). While a random network serves as a network-specific comparison benchmark, a small-world model is characterized by highly clustered nodes and a short average path length between nodes, and a scale-free model follows a power-law degree distribution among nodes (Basole & Bellamy, 2014). These topological differences between network models result in differing real-world SCN strengths and weaknesses. For instance, a SCN with small-world properties is robust to random failures but is sensitive to targeted disruptions such as economic sanctions (Nair & Vidal, 2011).

To date, MPP research has focused on I4.0 manufacturing flexibility and firm-level supply chain design modifications (R. Novais, 2019), and no research has attempted to take a network-level approach to MPP to maintain the interconnected, complex relationships between firms. For this research, the term firm is used in place of company or corporation. This study will survey three MPP firms to generate an approximate SCN topology and by examining the resulting network properties through qualitative analysis, find which of the two network types, scale-free or small-world, most accurately represents an MPP SCN. The author analyzes possible failure modes of the subsequent topological categorization based on established SC network theory research.

RQ1	What type of network topology most accurately represents a mass personalization supply chain network?
Hypothesis	Since MPP relies on configurable and efficient supply chains, MPP firms will be best represented by small-world networks.
Justification	Mass personalization SCNs require formal representation through a model that is conducive to analysis. This paper proposes a network-based approach.
Tasks	The author interviews three MPP supply chain managers using a qualitative protocol to guide the questioning and analysis. A graphical proxy representation of the supply chain network is created based on logical interpretations. The network will be categorized as either scale-free or small-world using foundational network metrics.

RQ2	How do disruptions impact MPP supply chain operations?
Hypothesis	Network topology and MPP technologies will contribute significantly to preventing external disruptions.
Justification	MPP firms should recognize potential failure modes caused by their unique production method.
Tasks	The author investigates how the resulting topological categorization withstands possible disruptions.

1.1 Study Motivation

COVID-19's continued disruption impact on SCNs has drastically increased lead times and costs for manufacturers and consumers, highlighting the need for robust and resilient SCNs. MPP, an emerging production method, has significant potential to increase consumer satisfaction and firm value via the inclusion of the consumer in the design process. This consumer input relies on I4.0 technologies to be a scalable and cost-effective method. Thus far, MPP research has focused exclusively on these technologies within a manufacturing setting, yet the scalability of manufacturing MPP products necessitates efficient, disruption-resistant SCNs. This study compares three existing MPP network structures and uses established network theory metrics to identify potential failure modes when presented with external disruptions. Current and forthcoming MPP firms may utilize the results to adjust their SCNs accordingly to remain robust and, if necessary, resilient.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature Review Overview

The following chapter provides the historical context for the emergence of mass personalization as an artifact of I4.0. The chapter describes supply chain network evolution and the representations for modeling their complex behavior. The last section lists the simulated disruption types and their effects on SCN resilience.

2.2 Industry 4.0

The newest industrial paradigm -- I4.0-- integrates digital, physical, and social spaces through Cyber-Physical-Social Systems (CPSS) (Gong et al., 2021; Morkos et al., 2021; Yang et al., 2022). With CPSS, manufacturing facilities utilize physical sensors, or Industrial Internet of Things (IIoT), to collect continuous data streams on human-machine and machine-to-machine (M2M) interactions (Zhang et al., 2018) using various technolologies (Morkos, 2012). This data, known as Big Data, is sent to cyberspace (i.e., cloud) for filtering, analysis, and real-time feedback execution (Yan et al., 2017). These systems provide the connectivity and efficiency to produce new manufacturing capabilities such as flexible modular factories, cobotic systems, digital twins, and advanced manufacturing techniques such as additive manufacturing (Dalenogare et al., 2018).

2.2.1 Manufacturing Paradigms Synopsis

As a consequence of emergent technologies and ideologies, all four industrial revolutions introduced novel production capabilities (Wang et al., 2017). With the development of steam power, the first industrial revolution introduced and standardized craft production (CP). Manufacturing products for a market-of-one, consumer requirements were fully met at a high cost and low production rates. The second industrial revolution came at the advent of electrical power and the resulting division of labor, product standardization, and the assembly line. Subsequently, mass production (MP) also takes advantage of economies of scale or the cost-benefit of higher production levels for one product. To meet the necessary scale, MP necessitates products designed for the market-of-many, forgoing individual consumers' needs to supply low-cost, low-variety products.

A precursor to mass personalization, MC emphasizes economies of scope over scale. Economies of scope imply that product variations lower average total cost (Tseng et al., 1996). **Figure 2.1** demonstrates MP's clear cost advantage at high production volume, which offsets the tremendous initial investment cost. However, consumers are willing to pay more to satisfy their specific requirements at low-to-medium production levels when the initial investment cost of MP is not feasible. MC fits this niche by utilizing market segmentation to provide variety and customization options. The third industrial revolution made MC viable for manufacturers due to cheaper computers and numerically controlled automated machinery. These technological advancements, along with the introduction of manufacturing management systems, such as product life management (PLM), facilitate product variations, or modules, that fulfill a more comprehensive range of stakeholder requirements. (Wang et al., 2017).

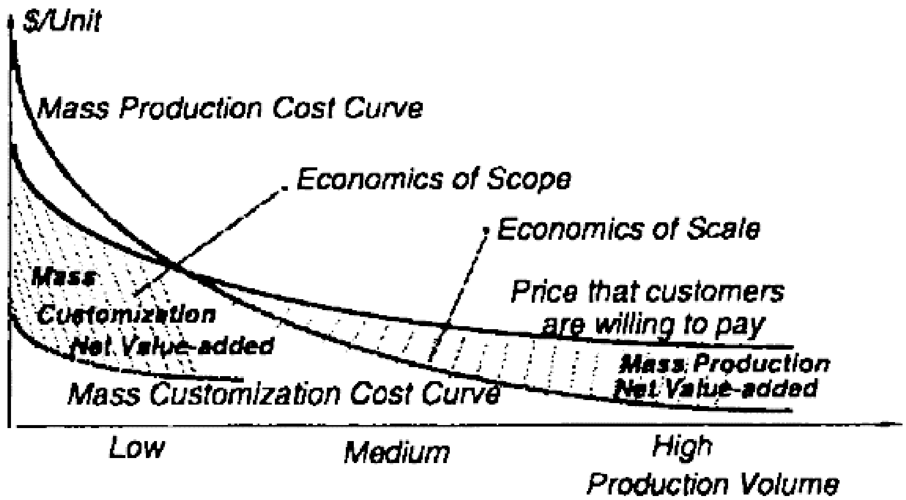

Figure 2.1 Economics of Mass Customization (Tseng et al. 1996)

2.3 Mass Personalization

While MC provides the consumer with a limited number of post-design product variations (market-of-few), mass personalization permits pre-design consumer input to create individualized goods (market-of-one). Personalized products can be traced back to CP, but as seen in **Figure 2.2**, MPP utilizes economies of scope to provide affordable fulfillment costs for producers and consumers (Kumar, 2007).

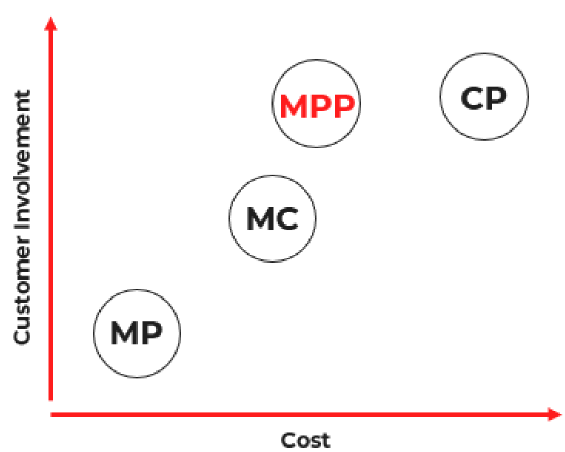

Figure 2.2 Taxonomy of production paradigms

Table 2.1 shows that both MC and MPP achieve the consumer's functional requirements. MC attempts to also capture affective requirements via marketing analysis. However, there must be an equilibrium between product permutation quantity and the seizable percentage of the market. Meanwhile, MPP elicits the consumer's affective and cognitive needs through active participation in the design process (Tseng et al., 2010). By capturing these latent needs, companies can gain a competitive edge with personalization which can drive a 5–15 percent increase in revenue (McKinney & Company, 2020).

Table 2.1 Differentiating factors between customization and personalization

Mass Customization	Mass Personalization
Consumer post-design choices	Consumer pre-design input
Product modularity (market-of-few)	Unique, individual product variations (market-of-one)
Consumer experience based on functional and affective requirements	Deals with affective, cognitive, and functional requirements

2.3.1 MPP Research & Implementation

Despite being conceptualized decades ago, MPP's implementation has been contingent on the recent development of I4.0 capabilities. **Figure 2.3** demonstrates that companies must generate heterogeneous products to remain competitive due to increased globalization. However, producing a different product per consumer with dynamic batch sizes requires a responsive, flexible manufacturing and supply chain system with a high degree of connectivity (Qin & Lu 2021). To the extent of manufacturing requisites, researchers have employed I4.0 technologies to propose specific solutions. Qin and Lu (2021) suggest that manufacturers use the self-organizing manufacturing system (SOMS) concept to achieve dynamic manufacturing job allocation. Ding et al. (2021) use IIoT's high-level connectivity between machines and people to realign production planning (ordering) and execution (manufacturing). For supply chain design, MPP's flexible product structure necessitates a network of reconfigurable suppliers, so Katoozian and Zanjani (2022) designed a quantitative decision model for creating such a network.

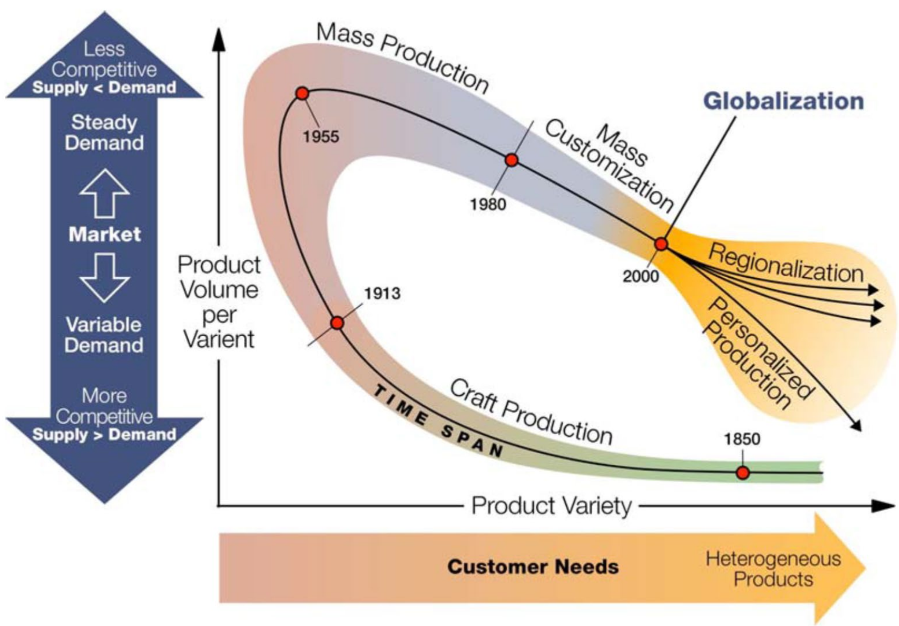

Figure 2.3 Manufacturing paradigms and their drivers (Koren 2010)

With all previously mentioned research, MPP companies serve as the FF, getting materials from suppliers and sending finished products to consumers. While this is similar to many MP and MC companies, the distribution of suppliers, manufacturers, distributors, and retailers for an MPP-based SCN is not well understood. Every MPP firm will differ in industry type, size, and product offering, but there has been little research towards formalizing commonalities, if any, that exists amongst MPP SCN topologies.

2.4 Supply Chain Representations

With the ongoing transition from the conventional vertically organized SC to the globally intertwined SCN, researchers have evolved representations of supply chain design. Supply chain analysis examines firm relationships as a vertical chain of the serial stages of production (suppliers, manufacturers, distributors, and retailers) and gives a macro-level, dyadic view of resource and information flows between production stages. Using this vertical chain assumption, researchers have studied SCs using static methods, including control theory, programming method, and queuing theory (Mari et al., 2015). However, these approaches do not demonstrate the dynamic, non-linear interdependencies between firms within the same stage. For example, original equipment manufacturers (OEMs) have direct suppliers (Tier 1), suppliers for Tier 1s (Tier 2), and often indirect raw material suppliers (Tier 3). Supply chain analysis would not capture the complex resource flows between suppliers. To solve this, Lazzarini et al. (2001) introduced the concept of a netchain. As seen in **Figure 2.4**, netchains comprise the vertical stages of production combined with the horizontal network of similar inter-organizational relationships. This approach allows for a holistic supply chain management (SCM) view.

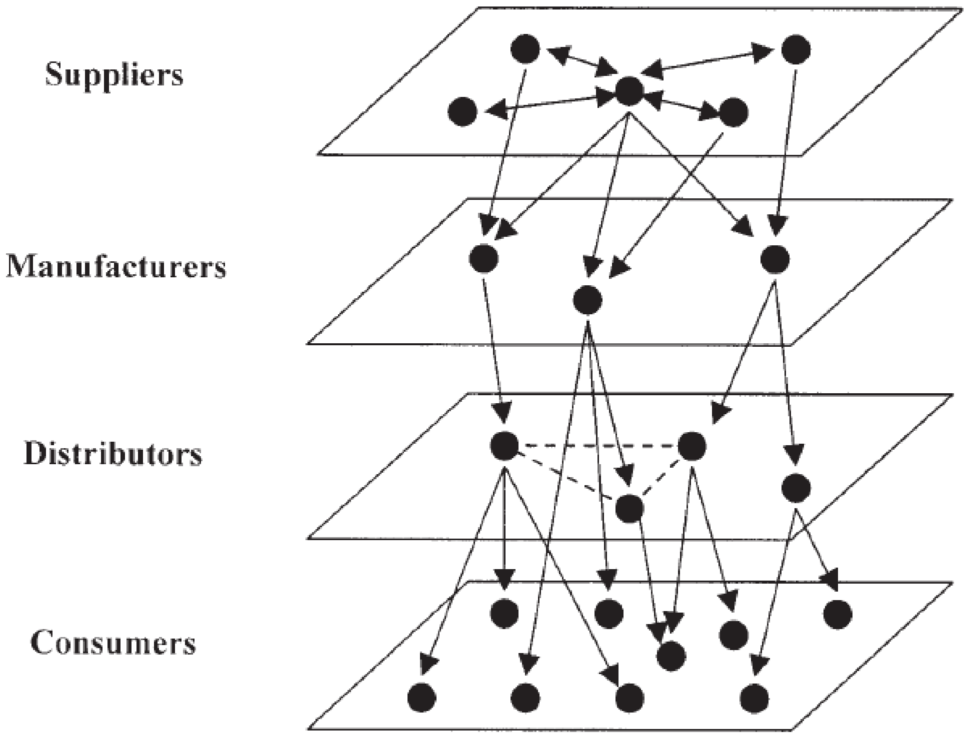

Figure 2.4 An example of a netchain (Lazzarini et al., 2001)

Although netchains provide an illustrative perspective of SCNs, researchers and supply chain managers require representations conducive to measuring node relationships and the effects of external perturbations. For example, highly connected SCNs such as the automobile industry have been combatting supply chain-related product shortages, especially in the past two decades (Trkman & McCormack, 2009). Researchers need to be able to model how these shortages impact the firms downstream. Furthermore, the ongoing supply chain crisis caused by the COVID-19 pandemic has affected local and global economies, making it challenging to determine disruption origin and diffusion (Ivanov & Dolgui, 2021). Therefore, this research employs network theory to model SCNs computationally.

2.4.1 Network Theory

Network theory, a science that evolved from graph theory in the 1960s, abstracts a given system as a weighted network $G = (N, L, W)$ of nodes N, representing autonomous entities, connected by links L (Erdos & Rényi, 1960). Links signify a relationship between two nodes and can be either *directional* or *unidirectional*, depending on the connection type. Each link can be assigned a weight, *W,* to represent the connection strength between two nodes (Fang et al., 2018). Researchers measure a network's degree distribution, characteristic path length, and clustering coefficient to understand node importance, node-to-node relationships, and topological classification.

A node's *degree,* k*,* refers to its number of links to other nodes and indicates a node's importance and visibility relative to other nodes. With Mari et al.'s (2015) undirected network *degree centrality* equation, shown in **Equation (1)**, *k* can be computed for a node using a square adjacency matrix, *A,* with rows, *i*, and columns, *j*, where $i, j = [1, \dots, N]$. Entry a_{ij} is equal to 1 if link l_{ij} exists; otherwise, the entry is 0. Summing the i^{th} row of *A* yields *k* for node *i*.

$$k_i = \sum_j a_{ij} \tag{1}$$

For network comparison, it is helpful to normalize the degree centrality by dividing k_i by the maximum degree $(N - 1)$ as seen in **Equation (2)**.

$$k_i' = \frac{k_i}{N - 1} \tag{2}$$

The *characteristic path length* or *closeness centrality, D,* indicates how central a node is within a network by measuring the shortest average path length to every other node. The closeness centrality shows how efficiently information can traverse the network; the lower the closeness centrality, the faster information can spread. Defined in **Equation (3)**, the closeness centrality of an undirected network is the reciprocal summation of the distance d between n_i and all other nodes N. Closeness centrality can be normalized by multiplying D_i by the maximum degree $(N-1)$ (Kim et al., 2011).

$$D_i = \left[\sum_{j=1}^{g} d(n_i, n_j)\right]^{-1} \tag{3}$$

The *clustering coefficient, C,* measures the transitivity of a node or the average probability that a local node is linked to two other nodes that are also connected. A fully connected node would have a C value of 1 (Mari et al., 2015). The clustering coefficient provides insight into subnetwork efficiency. To calculate the coefficient for node i, **Equation (4)** computes the ratio between the number of existing links L_i within degree k_i of nodes and the total number of nodes $k_i(k_i-1)/2$ (Albert & Barabasi, 2002).

$$C_i = \frac{2L_i}{k_i(k_i-1)} \tag{4}$$

The network clustering coefficient is then the average of all individual C_i,

$$C = \frac{1}{N}\sum_{i=1}^{N} C_i \tag{5}$$

Network theory is instrumental in identifying linkage patterns, interconnectivity between individual nodes, and global network performance and development (Basole & Bellamy, 2014). For instance, researchers have used network theory to predict the spread of epidemics (Meyers et al., 2006), growth of social networks (Newman, 2001), the structure of complex brain pathways (Bullmore & Sporns, 2009), and the response of ecological systems to predation and conservation disruptions (Sole & Montoya, 2001). SCNs share similar properties to these other real-world networks: high clustering coefficients, power-law connectivity, and short characteristic path lengths (Hearnshaw & Wilson, 2015). As such, the past decade of SCM research has relied on network theory to represent nodes as firms linked together, signifying a contractual (non-directional) or material flow (directional) relationship. Researchers can create complex graphical representations of real-world and proxy SCNs to test firm performance, firm-to-firm relationships, and network-level phenomena.

2.4.2 Topological Network Representations of Supply Chains

The aforementioned network metrics can be used to categorize any SCN structure as one of three topological network classifications presented in **Figure 2.5**: random, scale-free, or small-world (Nair & Vidal, 2011). SCNs are often structured as a ring lattice of n nodes linked together. Contrasting a regular network's ordered set of links between nodes, a random network (Gilbert, 1959) has a random set of connections. Since each node has an identical connection probability, most nodes have the same number of links, forming a Poisson degree distribution with low clustering and a short global characteristic path length. Real-world networks have much higher clustering, so random networks serve as benchmarks.

Watts and Strogatz (1998) proposed the ‘small-world’ network model as a realistic system representation, with a structure between regular and random networks. Instead of wiring nodes randomly, a small-world model initiates n nodes only connected to their k nearest neighbors in a clock-wise manner, and then with probability P_n, each link is rewired to another arbitrary node, with duplicate links forbidden. Otherwise, the link remains wired. Small-world networks retain high clustering properties inherited from regular networks and short average path length from random networks. Due to tight clustering, most nodes have a high number of connections, forming a Poisson degree distribution. Within the context of SCNs, high modularity of firms indicates the presence of a small-world topology.

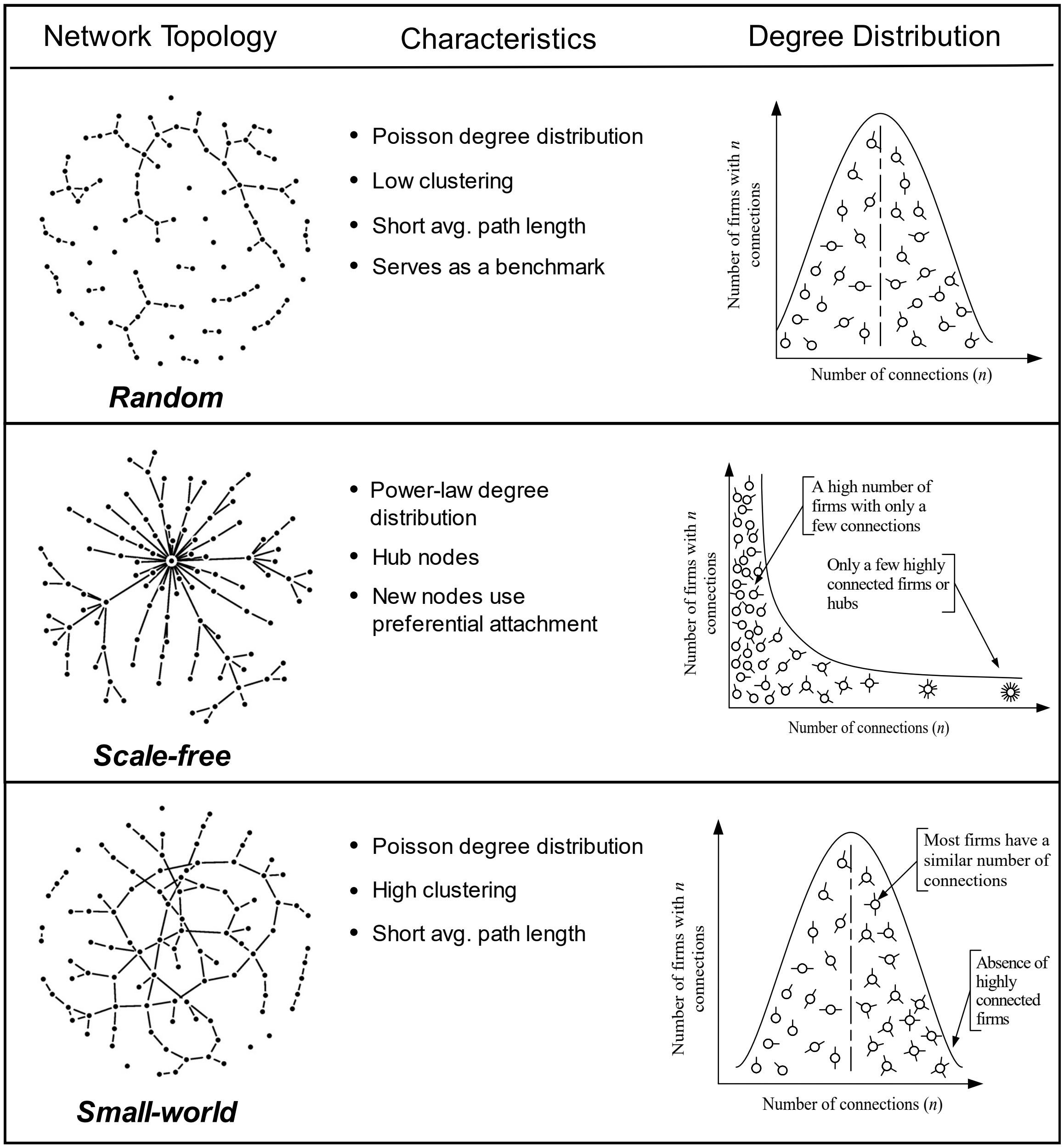

Figure 2.5 The three common network topologies with characteristics and degree distribution (adapted from Hearnshaw & Wilson, 2015; Airoldi et al., 2011)

Barabasi and Albert (1998) defined scale-free networks after graphing the internet's scale-free, power-law degree distribution, noticing that many new websites would preferentially link themselves to a few well-connected "hub" sites. A scale-free model begins similar to small-world, but new nodes connect with a probability P_n that is proportional to the degree of the target node. Whereas small-world SCNs have high firm modularity, scale-free SCNs have a few hub firms with many connections and many firms with only a few connections.

2.4.3 Network Topology Metrics

SCN research has primarily focused on how network topology affects performance when confronted with a disruption events, which generate significant operational risks (Stauffer, 2003). Random disruptions range from natural disasters, economic downturns, or epidemics, such as the ongoing COVID-19 pandemic. Targeted disruptions result from economic sanctions, piracy, cyberattacks, or global conflicts. Both types can quickly diffuse from firm-level to network-level, resulting in long-term interruptions. With increasingly complex globalized SCNs, risk propagation is largely unavoidable without robust and resilient SCs.

Robustness is a SC's ability to *resist* a disruption's impact while maintaining functionality. Individual firms can increase their robustness with excess inventory, supplier redundancy, and increased upstream visibility. Surplus inventory provides a buffer to continue operating when an external disruption occurs, but firms must balance this excess with the overhead cost, especially for time-sensitive products. Redundancy, measured by the closeness centrality, is key to increasing a network's robustness and resilience; if a supplier goes down, a backup source must be available to prevent downtime. Visibility is how well the firm can perceive an inbound external disruption and is increased when firms have relationships with suppliers outside of their direct connection.

Resilience examines a SC's capacity to *recover* functionality quickly after being disrupted. A firm is considered resilient if its SCN contains responsive, redundant firms. If an interruption does occur, redundancy provides multiple options for recovery. A network's responsiveness, measured by the closeness centrality and clustering coefficient, determines disruption response efficiency; a network with a low closeness centrality and high clustering coefficient allow for faster recovery and propagation of products and information (Nair & Vidal, 2011). This study will take a qualitative approach to investigate how these metrics impact the topology of a MPP SCN when faced with external disruptions.

2.5 Qualitative Analysis

There are three primary approaches to research: quantitative, qualitative, and mixed methods (Webster, 2007). Quantitative research involves testing objective theories by measuring numeric variables, whereas qualitative research involves collecting interview data from the subjects involved in the research inquiry. The data interpretation in this method relies solely on the research and the research team. Qualitative methods are used in various engineering design research. For example, Shah et al. (2019) and Kames et al. (2019) used a grounded theory qualitative approach to examine motivating factors impacting engineering capstone design students. Mixed methods integrate both forms of data collection (Creswell, 2013).

The researcher chooses the approach based on the data type required to answer the research question(s). In the case of building a computational proxy model of MPP SCN, quantitative data is preferred; however, SCN quantitative data is notoriously difficult to obtain. Firms build competitive advantage by keeping relationships secretive and have no incentive to reveal specific supplier and distributor associations. Past SCN research has relied on databases such as the Bloomberg terminal to examine large, publicly-traded firms (Basole & Bellamy, 2014; Brintrup et al., 2017; Li et al., 2020). However, mass personalization is a new form of production; therefore, firms employing MPP are also new and lack sufficient publicly-available SC documentation. For this reason, this study uses a mixed-method approach to gather both quantitative data about the number of firms in a network to answer RQ1 and qualitative data about relationships and disruptions, informed by three MPP SC experts, to answer RQ1 and RQ2.

There are five approaches to qualitative research: narrative, phenomenological, ethnography, grounded theory, and case studies. The narrative approach examines an event through a narrative lens of the interviewees' lived experiences (Andrew et al., 2013). Phenomenological research is interested in the essence of shared experiences concerning a phenomenon, searching for a common meaning or belief (Boland, 1985). Ethnography studies patterns of cultural groups' shared beliefs and languages, typically through interviews and observations (Creswell, 2013). Grounded theory is an iterative, inductive approach; the researcher derives themes in collected participant data and, through iteration, constructs a theory about the data's interrelationships (Chun Tie et al., 2019). Case studies are appropriate for researching emergent areas of interest and investigating real-world phenomena via contextual data gathered from relevant stakeholders (Benbasat et al., 1987; Scheibe and Blackhurst, 2018). This research uses a grounded theory approach to discover interrelationships between firms; therefore, the rest of the background will be from a grounded theory perspective.

With grounded theory, researchers interview stakeholders to gather detailed answers using pre-defined interview questions, occasionally revealing profound insights. The interviewer must choose between unstructured, semi-structured, and structured interviews. Unstructured interviews have a general goal, but the responses and discussion are open-ended. While unstructured interviews are favorable in open-ended research questions such as narrative and phenomenological studies, the lack of interview structure can lead to inconsistent questions and answers. Semi-structured interviews use standardized questions to guide the discussion while utilizing probes to correct deviations from the initial prompt, permitting rigorous, in-depth data collection about a stakeholder or topic. Structured interviews are primarily used for large-scale generalized data collection since the questions and order are entirely fixed (Clark et al., 2019). Further, the research group possess background with performing semi-structured interviews and developing coding schemes (Bassette et al., 2014; Morkos et al., 2015; Bassette et al., 2016; Kames et al., 2018).

2.6 Reliability and Validity

Qualitative analysis requires a rigorous framework and verification strategies to maintain its utility. Both scientific paradigms, qualitative and quantitative, ensure rigor through reliability and validity, despite different verification strategies. Reliability is the consistency of a research method, whereas validity is the method's accuracy. A method might be reliable but not valid if it measures something with consistency but measures the wrong construct. For qualitative research, Whitemore, Chase, & Mandle (2001) further broke validity into four components: credibility, authenticity, criticality, and integrity. The research is credible if the results accurately reflect the participants' experiences, and it is authentic if the results represent the subtle differences between participants' input. The research process must establish evidence of the researcher's critical appraisal and integrity, humbly acknowledging the possibility of error.

The researchers' responsiveness ultimately determines the reliability and validity of an evolving study. A responsive researcher constantly checks the research schema for potential flaws and remains open to changing any poorly supported ideas, no matter their predispositions. Lack of responsiveness may also be due to unfamiliarity of the research area, over-adherence to instruction without regard to data, inability to abstract or synthesize data coding, and failure to relinquish personal bias (Morse et al., 2002).

2.6.1 Developing an Interview Protocol

To promote responsiveness, researchers employ various verification strategies throughout the research process. One such verification strategy is methodological congruence or the alignment of the research questions with the methodology. In qualitative analysis, an interview protocol provides a systematic framework in which a researcher aligns interview questions with research questions, strengthening the reliability of the interview. Protocols guide the interviewer through the introduction, questioning, and closing remarks. With a semi-structured interview, the protocol guarantees that the questions and any necessary probes remain organized yet open-ended so that the full extent of the interviewee's experiences are documented. The selected interviewees should also be well-informed of the research topic, another verification strategy. Organized questions ensure a natural progression of questions, allowing for a comfortable, conversational interview. A protocol also keeps the conversation focused and limited to a predetermined duration, respecting the interviewee's time and attention.

Beyond the interview structure, the trust and well-being of the interviewee are essential characteristics to consider so that they feel comfortable sharing their experiences. The introduction should include an explanatory summary of the interview's purpose, an interview outline, and the intended usage of the interviewee's answers. The interviewer should also request consent to use the interviewee/firm's name (if applicable) and record the conversation. An audio recording of responses is encouraged to remain attentive to the interviewee; it also prevents loss of contextual information in later analysis. If the interviewee does not consent to a recording, the interviewer should be ready to take detailed notes. The interviewer should not interrupt while the interviewee speaks and use non-verbal expressions to display understanding. The interviewer should also ask clarifying questions when necessary (Rubin & Rubin, 2012). The interviewer's closing remarks should ask for questions, convey genuine gratitude, and have a timeline to follow up with findings.

2.6.2 Coding Scheme

The coding of interview data is an iterative, analytical process used to identify data themes. Coding reliability and validity are established throughout the procedure with incremental verification steps such as deciding a unit of analysis, developing a coding scheme, determining the coder organization, training coders, and choosing an appropriate reliability index to compare codes (Syed & Nelson, 2015). Before coding commences, the researcher must decide on coder organization and reliability index to avoid compromising the procedure's integrity.

Coder organization refers to each coder's role during the procedure and how to resolve any disagreements. One such organization is where one "master" member codes the entire data set while a reliability coder only codes a random portion of the data. The exact proportion is dependent on the sample size required to generalize and calculate the reliability coefficient confidently. Only the master coder's codes are used in the final analysis (Syed & Nelson, 2015). Another coder organization uses two or more coders to code the entire data set separately and then come together after the final coding phase to discuss each code. The final set of codes is an amalgamation of multiple coder input. A third party familiar with the research and coding manual can resolve any code disagreements.

Before coding commences, the coders become familiar with the data before official coding begins (Braun & Clarke, 2006), noting any intriguing ideas. By this time, the coders should have decided on the unit of analysis - in other words, what portion or type of qualitative data will receive a code. The unit of analysis keeps the coding process scoped. Finally, the coding scheme is developed either deductively (top-down) or inductively (bottom-up), contingent on the qualitative approach and research question(s).

The grounded theory approach is an inductive coding scheme that occurs in initial, intermediate, and advanced phases. Initial coding involves labeling as many meaningful words or sentences as necessary and noting emerging patterns. The intermediate phase abstracts the initial codes into categories based on similar properties. This phase requires the coders to reassess their codes continuously and with theoretical sensitivity, leading to the development of main categories. Once all categories have been identified, the coders should move to the final phase, described as theoretical saturation (Chun Tie et al., 2019). In this advanced phase, coders further abstract the categories into primary and secondary themes, forming a coherent theory enforced by relevant codes. With the advanced phase finished, coders meet together and reveal their final codes, using a predetermined reliability index to calculate interrater reliability.

2.6.3 Reliability Index

Interrater (inter-coder) reliability measures agreement between final codes developed by diverse researchers who analyzed the same data corpus (Lavrakas, 2008). This coefficient further enforces consistency and reliability. There are various reliability measurements, and the researcher should choose one (or multiple) based on the coding scheme. Defined in **Equation (7)**, the simplest method is the *Percentage Agreement,* P_A which is the number of codes the coders agreed upon (N_A) divided by the total number of codes, multiplied by 100. N_D is the total number of disagreements.

$$P_A = \frac{N_A}{(N_A + N_D)} * 100 \tag{7}$$

Percentage agreement provides a simple, literal representation of coder agreement, but it fails to measure the possibility that researchers agreed upon a code by chance. This limitation does not invalidate the method, and for large, open-ended narratives, percentage agreement provides an appropriate measurement. However, to account for chance, coders often use Cohen’s kappa (κ) to calculate the proportion of agreement not due to chance, making it a conservative measurement (Cohen, 1960). **Equation (8)** is the formula for kappa:

$$\kappa = \frac{P_o - P_c}{1 - P_c} \tag{8}$$

P_o is equivalent to P_A from **Equation (7)** without multiplying by 100. The index of chance, P_c is removed from both the nominator and denominator, effectively eliminating chance from the equation. Researchers can interpret the kappa values using **Table 2.2**; Alternatively, Bakerman & Gottman (2019) recommended using a lower bound of $\kappa = 0.70$ for acceptable agreement.

Table 2.2 Kappa Interpretation (Viera & Garrett, 2005)

Kappa	**Agreement**
< 0	Less than Chance
0.01 – 0.20	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 0.99	Almost Perfect

In addition to reporting multiple indexes, researchers should also include a confusion matrix of the coders' agreements/disagreements. This matrix provides further insight into how each index is calculated, and potential coding patterns. For example, if a coder generates drastically more or less codes than other coders, the disparity may impact the kappa or percentage agreement (Syed & Nelson, 2015).

2.7 Summary of Current State of Knowledge

Existing research demonstrates that MPP, a value-adding integration of the consumer into the design process, requires flexible, efficient manufacturing and distribution methods to be a viable option. However, it remains unclear if such a method results in a particular SCN type or how network type affects an MPP SCN's robustness or resilience when disrupted. This work investigates the SCN type and disruption events through interviews developed by a reliable and valid interview protocol.

CHAPTER 3

METHODOLOGY

3.1 Methodology Overview

This chapter begins with MPP interviewee selection process. Then, Section 3.3 describes the development of the interview protocol and explains the final interview questions in detail. Section 3.4 details the interview timeline and data collection methods, and Section 3.5 presents the coding procedure and specifies reliability indexes. Finally, Section 3.6 explains how the qualitative and quantitative data from the interview process is used to develop the nodes and links to form the MPP SCN topologies.

3.2 Selecting Interviewees

To create a proxy network, this research requires data for every firm and their relationships within an MPP SCN; multiple MPP SCN samples are necessary for the results to be considered truly representative. Without reliable and publicly available quantitative MPP SC data, this study gathered information from the perspective of authentic MPP firms, referred to as Focal Firms (FFs). The firms supplied quantitative data about the number and type of firms in their network, with qualitative relational information to inform every firm's interrelationships. Initially, a survey was considered to collect data, but participants could misunderstand questions, provide insufficient detail, or neglect participation. Instead, a semi-structured interview was chosen due to its informal, flexible nature; the interviewer could ask clarifying questions and record nuanced answers from SC experts, providing an opportunity to glean deeper insights than would be possible with a survey.

The researcher had to identify potential MPP FFs to interview. There were two primary factors considered when classifying a FF as MPP:

1. Does the FF include the consumer within the design process?
2. Can the FF produce its product(s) in a scalable, efficient manner?

The second factor prevented craft-production FFs from being selected. Past MPP research, articles mentioning MPP, and online keyword (i.e., mass personalization, personalized products, personalization) searches were used to discover potential interviewees.

A thorough search identified eight potential FFs that fit the criteria based on available data describing their production methods. While more MPP FFs certainly exist, the search was limited by time, and its cessation was justified by the number of firms interviewed in past qualitative SCN research (Scheibe & Blackhurst, 2018). The FFs' sizes ranged from small to large, with various industry types. Previous SCN research used financial databases to inform their network topology, so before requesting an interview, each MPP FF was input into Bloomberg Terminal SPLC[1], a global supply chain database, to determine if a listing with quantitative relationship data existed. Only one FF (Xometry) returned information, but the data was solely incorporation records with no concrete supplier data.

Each FF was contacted through website forms or company email. All requests contained a short description of the research goals, a specific request to interview the

[1] https://blinks.bloomberg.com/screens/splc

firm's SCN expert, and the expected duration of the interview. Only three responded out of the eight FF, but each agreed to an interview with their SC expert. All three interviewees consented to having their name and firm's name used, and a short description of each is provided to illustrate their unique MPP production.

Ministry of Supply (MoS) is an apparel firm with a hybrid online and brick-and-mortar presence. Part of their line uses an on-demand 3D knitting machine that manufactures personalized garments to the customer's exact specifications without any seams, increasing the garment's durability. Beyond personalization, the process produces less fabric waste and prevents stagnant inventory.

ProtoJet is an on-demand manufacturer specializing in injection molding and toolmaking. Customers upload their designs and choose the part quantity. If there are no issues with the design, ProtoJet manufacturers the parts in-house, and the part quantity can scale from one-offs to thousands.

Xometry is an on-demand distributive global marketplace where customers upload their designs and choose from various manufacturing capabilities. After selecting their part quantity, Xometry's artificial intelligence checks the customer's "technical package" for manufacturability and then matches the customer with several potential partner manufacturers based on specific characteristics such as geographical distance, manufacturing capabilities, and part quantity. If the top choice manufacturer declines the job, the following potential manufacturer is given the opportunity. If there is a product issue, Xometry is the responsible party.

3.3 MPP Interview Protocol

Prior to the interviews, an interview protocol was developed using the Interview Protocol Refinement Method (IPR) (Castillo-Montoya, 2016). IPR provides a rigorous four-step framework to develop a research instrument capable of obtaining high-quality interview data. **Table 3.1** briefly explains each phase:

Table 3.1 The four IPR phases and purpose (Adapted from Castillo-Montoya, 2016)

Phase	Purpose of Phase
Phase I: Ensuring interview questions align with research questions	To create an interview protocol matrix to map the interview questions against the research questions
Phase 2: Constructing an inquiry-based conversation	To construct an interview protocol that balances inquiry with conversation
Phase 3: Receiving feedback on interview protocol	To obtain feedback on interview protocol (possible activities include close reading and think-aloud activities)
Phase 4: Piloting the interview protocol	To pilot the interview protocol with a small sample

The last two phases allow for recursive refinement of the first two phases, producing a reliable and valid set of interview questions.

3.3.1 Research Question Alignment

The first IPR phase is a form of methodological congruence, a critical reliability verification process: the interview questions are aligned with the research questions. The IPR calls for a research-interview question matrix to support the alignment process; the matrix provides a visual guide to identify potential gaps or redundancies while brainstorming and writing the interview questions. First, the request questions were abstracted into the following broad categories: SCN makeup, SCN selection, robustness, resilience, and disruptions. Then, in the order of each group, interview questions were developed to elicit the necessary information from an interviewee.

The research matrix, seen in **Table 3.2**, contains the initial questions, marked with black Xs, and the questions finalized in Phase 4, marked in blue. This table does not represent the total number of iterations required to refine the questions, but it reveals the protocol's drastic development from Phase 1 to Phase 4's completion. While some SCN structure-related questions were direct and quantitative, most questions were open-ended. The preliminary matrix contained short introductory and basic transitionary statements, but it lacked a conversational flow. All of the initial questions can be found in **Appendix A**.

Table 3.2 IPR Question Matrix

Research Themes

Interview Questions	Background Information	SCN Makeup	SCN Selection	Robustness	Resilience	Disruptions
IQ1	X					
IQ2	X					
IQ3	XX		XX			
IQ4		XX				X
IQ5		XX				
IQ6		X				
IQ7			XX	X	X	
IQ8		XX	XX	XX		
IQ9		XX				
IQ10		XX		XX		
IQ11			X		X	
IQ12					XX	
IQ13					XX	XX
IQ14				XX	XX	XX
IQ15		XX	X		XX	XX
IQ16		X				X
IQ17	X					X
IQ18	X					

Key
X: Existing Interview Questions
X: Refined Interview Questions

3.3.2 Constructing Inquiry-based Conversation

While Phase 1 develops the key interview questions, Phase 2 provides an even, conversational distribution of introductory, transitionary, key, and closing questions. Introductory questions set the interview's tone and allow the participant “warm-up” while transition questions keep the conversational tone. These questions provide a comfortable interview setting conducive to producing deeper insights; if the interviewee feels comfortable, they are more likely to provide detailed responses. At this phase, the researcher added a background information group to cover introductory and closing questions. The introductory script was also modified to include the necessary consent prompts.

3.3.3 Receiving Feedback on Protocol

Phase 3 requires the researcher to receive critical protocol feedback from a colleague or research team, enhancing the instrument's reliability. The feedback should examine the protocol’s length, structure, flow, wording, and general question comprehension; to assist, the IPR provides an Activity Checklist, presented in **Table 3.3** Activity Checklist for Close Reading (Castillo-Montoya, 2016), for each colleague to fill out.

The researcher for this study received feedback from five lab mates during an hour-long lab meeting. Each member was given an Activity Checklist, and the researcher went through the entire protocol while receiving verbal feedback. After the meeting, the researcher collected all five checklists presented in **Appendix B**. The comments were critical of the short introduction, absence of ending questions/closing remarks, technical jargon, confusing wording, and the absence of probes for open-ended questions.

Table 3.3 Activity Checklist for Close Reading (Castillo-Montoya, 2016)

Aspects of an Interview Protocol	Yes	No	Feedback for Improvement
Interview Protocol Structure			
Beginning questions are factual in nature			
Key questions are majority of the questions and are placed between beginning and ending questions			
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments			
A brief script throughout the interview protocol provides smooth transitions between topic areas			
Interviewer closes with expressed gratitude and any intents to stay connected or follow up			
Overall, interview is organized to promote conversational flow			
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)			
Only one question is asked at a time			
Most questions ask participants to describe experiences and feelings			
Questions are mostly open ended			
Questions are written in a non-judgmental manner			
Length of Interview Protocol			
All questions are needed			
Questions/statements are concise			
Comprehension			
Questions/statements are devoid of academic language			
Questions/statements are easy to understand			

The researcher made the necessary corrections to resolve confusing wording, add probes and closing questions, and revise the introduction.

3.3.4 Performing a Pilot Interview

Whereas Phase 3 is an open, informal critique of the protocol, Phase 4 simulates an authentic interview in realistic conditions through a pilot test with a representative participant. The participant does not provide feedback on the protocol; instead, the researcher notes any protocol shortcomings such as misunderstanding questions, lack of probing questions, and interview length.

The researcher for this study performed a pilot interview with their principal investigator, who is knowledgeable about SCNs. The test was conducted through a web-based conferencing platform and timed. While the interview flow was sufficient, some questions were too open-ended. For example, the original protocol asked, “Are there specific preferences when choosing a new/replacement supplier, distributor, or retailer?” leading the participant to ask what circumstances would lead to replacing a partner. To prevent this confusion, an additional statement, “Say a disruption like COVID-19 makes you have to switch to a new supplier” was added. The rest of the revisions are highlighted in the final interview protocol found in **Appendix C**.

3.3.5 Final Interview Protocol

This section briefly discusses the reasoning behind the eighteen questions in the final interview protocol. The protocol comprises four primary sections: introductory, SCN structure, disruptions, and closing questions. The introductory section begins with three general questions. The first two questions, shown in **Figure 3.1,** confirm the role and expertise of the interviewee, while the third ascertains the firms’ competitors to understand the firms’ industry type and size.

Interviewee Introduction *I'd like to start by asking you a few general questions.*
IQ1. How long have you been with COMPANY NAME*?* IQ2. What is your current role within COMPANY NAME*?* ***Probe*****:** How familiar are you with your supply chain network? IQ3. What type of companies are your primary competitors?

Figure 3.1 Introductory interview questions

In **Figure 3.2**, a transitionary statement shifts the conversation toward SCN structure related to the RQ1. IQ4 is open-ended so that the interviewee would detail their SCN from various perspectives, such as financial or geographic. However, a probe about geographical distribution was added in case of confusion.

COMPANY's **SCN Structure** *Thank you for sharing information about your background. I'd like to transition to talking about how COMPANY supply chain network.*
IQ4. How large is your SCN? *This could be a rough estimate* ***Probe*****:** *Is it a global SCN?*

Figure 3.2 SCN question about firms' size and geographical distribution

Displayed in **Figure 3.3** are questions related to the quantity of suppliers, manufacturers, distributors, and retailers. IQ5 directly requests the FF's number of facilities, assuming they act as manufacturers. Since not all firms have distributors or retailers, IQ6 first questions how a finished product gets to its destination. Then, if necessary, a probe ascertains the exact distributor and/or retailer count. IQ9, while grouped with other supplier-related questions, also requests specific data on the number of tiers (if any) and suppliers.

IQ5. How many COMPANY NAME manufacturing facilities operate?

IQ6. When a product leaves your facility(s), what are all the ways it can get to the consumer? *Straight to consumer, through a distributor, from a retailer, hybrid, etc.*
***Probe if dist. or retailer exists**: How many distributors and/or retailers are in your network?*

IQ9. How many tiers deep is your supplier network?
***Probe**: Do you know a rough estimate of the total number of suppliers in your SCN?*

Figure 3.3 Specific questions to elicit quantitative data about the SCN firms

Whereas the questions in **Figure 3.3** address the SCN nodes by requesting quantitative data, the questions in **Figure 3.4** determine how those nodes are linked through questions related to degree distribution, closeness, and clustering. IQ7 asks how the FF preferentially attaches to new firms, revealing if there are key firms with a higher degree of connections. IQ8 examines the FF's redundancy, which is related to the robustness and closeness centrality of the network. For instance, if the FF has multiple Tier 1 suppliers for the same component, each supplier acts as a pathway to the components' raw material supplier(s). IQ10 and IQ11 investigate the SCN's clustering by questioning supplier-to-supplier and supplier-to-competitor relationships. FFs that have highly connected suppliers will have SCNs with higher transitivity.

IQ7. Say a disruption like COVID-19 makes you have to switch to a new supplier. Are there specific preferences when choosing a new/replacement supplier, distributor, or retailer?
    Probe: *Preferences could include geographical location, company reputation or age, cost of business, etc.*

IQ8. Faced with a disruption, do you have redundancy in your supply chain?
    Probe: *Where is there redundancy and why?*
    Probe: *Is that normal practice?*

IQ10. Do you know if your suppliers communicate or collaborate with each other?
    ***Probe*:** *If so, is it across supplier tiers?*

IQ11. Do your competitors use the same suppliers?

Figure 3.4 Link-related questions

IQ12, presented in **Figure 3.5**, is primarily concerned with the FF's resilience after a significant disruption. However, similar to IQ7, the probe questions if certain suppliers are more important, i.e., degree.

IQ12. How quickly could you recover if a supplier were to go OOB overnight?
    ***Probe*:** *Are there certain suppliers whose going OOB would affect you more than others?*

Figure 3.5 Supplier significance questions

IQ13 and IQ14, displayed in **Figure 3.6**, transition the interview to RQ2's disruption-related questions. IQ13 requests specific example(s) of an easy and hard disruption they experienced, with COVID-19 as an illustrative case. IQ14 continues with the previous example(s), but it is interested in the FF's level of visibility of the incoming disruption(s).

Disruptions *Thank you for sharing information about COMPANY's supply chain. I'd like to transition to talking about COMPANY's history of overcoming disruptions such as COVID-19*

IQ13. Please tell me about an example of an "easy" disruption that you were quick to recover from. Why was it easy?
Use a supplier shortage or missed deadline here if needed
    Probe**:** *Same question, but hard. Use COVID-19 here if needed*
    Probe if short answer**:** *How did you recover?*
 	
IQ14. In those examples, did you know the origin of the disruption or was it network-wide?
    Probe**:** If you know the origin, was it upstream/downstream?

Figure 3.6 Disruption experience questions

While the motivation of the questions thus far has been to create a proxy SCN inductively, the interviewees are SCN experts, so IQ15 and IQ16, displayed in **Figure 3.7**, elicit their perspectives. IQ15 examines the interviewees' perception of the SCN structure's impact on recovering from a disruption. IQ16, without any network-specific terminology, asks which topology best represents their SCN. This question will assist the researcher when developing the proxy networks.

IQ15. Do you think the makeup of your supply chain network impacts how quickly you can recover from a disruption?

***Probe*:** If so, could you provide any examples?

IQ16. Below are two supply chain networks with each dot representing a company and each line representing a relationship. The blue dot signifies your company. Which network do you believe best represents your SCN?

Probe: *Why?*

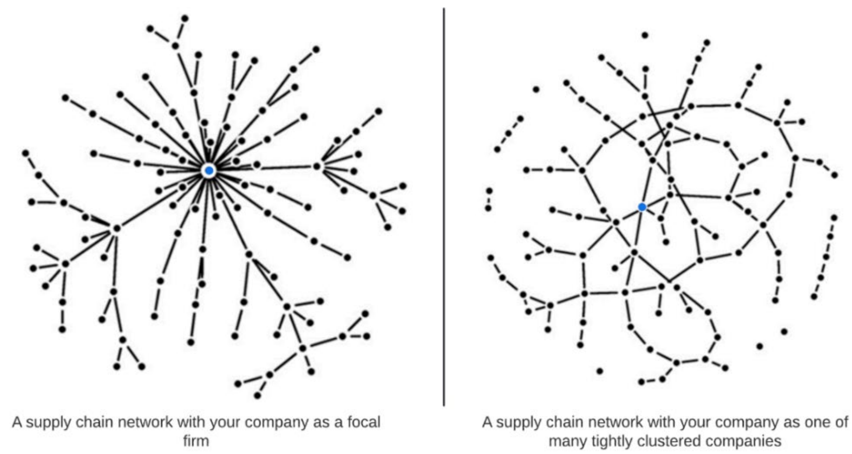

Figure 3.7 Questions to prompt interviewee's perspective of their SCN structure

Figure 3.8 contains the two closing questions. IQ17 gathers the interviewee's perspective on the most relevant questions regarding SCN disruptions, and IQ18 allows the interviewee to speak freely or ask questions.

IQ17. As an expert in the field, what are relevant questions that you think we should be asking other companies like yours as it relates to disruptions? What would you like to know about your counterparts in other corporations?

IQ18. Do you have any comments, or questions for me?

Figure 3.8 Closing questions

3.4 Conducting the Interviews

The three interviews were conducted over two weeks, in the order of Ministry of Supply, ProtoJet, then Xometry. While grounded theory calls for any necessary revisions to the protocol between 45-minute interviews, the IPR elicited the appropriate answers without modification or clarification. Each interview was recorded and subsequently transcribed by an online transcription service.

3.5 Coding Interview Data

Before commencing the coding phase, the researcher became familiar with the data and read through the transcription. Notes, found in **Appendix D**, were taken of any pertinent information. All three transcriptions were combined into one Word document, separated by interviewee name. The free, open-source coding software Taguette[2] was used throughout the coding process.

Before the interviews, the researcher requested coding assistance from a labmate who had previous experience coding qualitative data and familiarity with the research questions. Serving as co-coders, each member coded the entire transcription through the three grounded theory coding phases: initial, intermediate, and advanced. To verify that both members understood the appropriate unit of analysis, coders coded the first interview transcription and compared the initial codes, revealing a consensus on the coding objective. After this verification, the coders did not share or discuss coding until after the advanced phase.

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[2] https://www.taguette.org/

3.5.1 Interrater Reliability

After the final coding phase, the two coders met to deliberate their coding themes; the goal was to condense both code sets into a single, unified thematic narrative, with interrater reliability indexes used to verify coder agreement. Whereas unstructured interviews necessitate reviewing each coded quote, a well-defined set of interview questions permits the coders to focus solely on the derived code themes. Before the coding commenced, Cohen’s Kappa, percentage agreement, and a confusion matrix were decided as the indexes used to calculate reliability. Both sets of initial code themes were analyzed and compared using the respective coded excerpts.

Table 3.4 shows both code sets with an agreement column for each. If both coders agreed that a code should be included in the finalized set, the agreement column was marked Yes, Yes (Y,Y) for coders 1 and 2, respectively. Likewise, if they agreed that a code did not yield significant meaning relating to the research goals, it was marked No, No (N, N) and discarded. However, if the coders disagreed on a code’s meaning or significance, it was marked either Yes, No (Y, N) or No, Yes (N, Y) and was later accessed by the P.I. and researcher. To avoid inflating the reliability index scores with false agreements, codes with similar meaning or origin were merged and marked accordingly. After finalizing the codes, the four score types were tallied and used to calculate the reliability indexes.

Table 3.4 Initial code sets

Coder 1	1, 2	Coder 2	1, 2
Competitors	Y,Y	Company Scale	Merged
Consumer	Y,Y	Company Type	Merged
Consumer.Global	N,N	Company position in supply chain	Merged
Disruption Effect	Y,Y	Competitors	Merged
Disruption.COVID	Y,Y	Consumers	Merged
Disruption.LeadTimes	Y,Y	Covid-19 Disruptions	Merged
Disruption.Origin	Y,Y	Disruption Experience	N,Y
Disruption.ManfacturingCost	Y,Y	Distribution	Merged
Disruption.Shipping	N,N	Distributors	Merged
Distributors	Y,Y	Community Engagement	N,Y
Distributors.3PL	Y,Y	Familiarity with supply chain	Merged
Distributors.Direct2Consumer	Y,Y	Identifying supply chain network	Merged
Experience	N,N	Interviewee's experience	Y,Y
Manufacturing	Y,Y	Interviewer's career	N,N
Manufacturing.Global	N,N	Manufacturing.Locations	Y,Y
Manufacturing.OnDemand	Y,Y	Raw material	Merged
SCN	Y,Y	Raw material suppliers	Merged
SCN.ScaleFree	Y,Y	Recovery Time	N,N
SCN.SmallWorld	Y,Y	Redudancy	Merged
Redundancy	Y,Y	Redundancy Recovery	N,N
Resilience	Y,Y	Role	Merged
Distributors.Retailers	Y,Y	Scale free network	N,N
Robustness (+/-)	Y,Y	Scale of Supply Chain	N,N
Robustness.Suppliers	Y,N	Small world network	Merged
Suppliers	Y,Y	Supplier Factors	N,N
Suppliers.Clustering	N,N	Supplier qualification	N,N
Suppliers.Locations	Y,Y	Suppliers and Competitors	Merged
Suppliers.Selection	Y,Y	Supply difficulties	N,N
Suppliers.Tiers	Y,Y		
Visibility	Y,Y		
Visibility.Competition	N,N		
Visibility.Suppliers	Y,N		

3.6 Representing and Comparing MPP SCN Topologies

To answer RQ1, each firm's SCN was computationally modeled and analyzed for topology similarities. The procedure to generate each topology with quantitative and qualitative data is outlined in the following subsections. Gephi[3], an open-source graph tool, was used to visualize and analyze the network topologies (Bastian et al., 2009). GephiStreamer API[4], a Gephi plug-in for streaming external data, connected a Python script to Gephi to visualize each firm's network. A random graph of comparable network size was produced for each topology as a benchmark; SCN topologies would have a significantly higher clustering coefficient and closeness centrality than a random network. Each topology's degree distribution was plotted on a double logarithmic (log-log) scale and examined for a power-law linear curve, indicating if the topology is scale-free or small-world (Strogatz, 2001).

3.6.1 Quantitative – Firm Nodes

Each interview transcript was scanned for quantifiable data regarding the network's node quantity and type. Each firm's network node data, displayed in **Table 3.5**, was labeled accordingly, with suppliers divided into the tier system if relevant to the FF. These data points inform the network's node topology.

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[3] https://gephi.org/

[4] https://github.com/totetmatt/GephiStreamer

Table 3.5 Network node quantity and type

Firm Name	Suppliers			FF	Distributors	Retailers
	T3	*T2*	*T1*			
MoS	7	15-20	5-7	1	0	1
ProtoJet		35-50		2	10-15	0
Xometry		5000		6	0	0

3.6.2 Qualitative

Since this study focuses on the FFs' SCN structure from a network-wide perspective, the links between the firm nodes were simplified to represent existing unweighted relationships. Unlike directed financial or material flows, a relationship link is undirected and can signify a competitive or collaborative connection. To develop these relational links without quantitative data, the transcript was scanned for quotes regarding the three standard SCN metrics used to describe network characteristics, notably node interrelationships: degree, closeness, and clustering; the subsequent subsection briefly demonstrates this process. While interview questions 7, 8, 10, and 11 were designed to elicit link relationships, other questions may be referenced for relevant quotes. Furthermore, IQ16, where interviewees self-identified their network, was also used to indicate network links. The researcher used the derived metrics and interviewee perspective to develop an approximate network.

3.6.3 Network Links

In **Table 3.6**, every row contains a select number of quotes (and question origin) pertinent to each firms' network degree. These quotes provide insight into whether specific firm(s) are significant and have a higher number of connections. MoS has Tier 1s, referred to as middlemen, that most other apparel factories also have to go through, indicating a higher degree; in particular, one of the Tier 1s provides a substantial percentage of MoS's line. The FF also has strong connections to its mills (Tier 3s), signifying links connecting the FF to Tier 3s both directly and through the traditional downstream method. ProtoJet considers itself a Tier 2, mainly dealing with raw material suppliers (Tier 3s) and sending finished parts to distributors or consumers. Lastly, Xometry serves as an on-demand manufacturing platform, so its "suppliers" are technically manufacturers. Since Xometry has facilities to handle quality assurance and consumer-related issues, they are the middleman connecting consumers to manufacturers.

Table 3.6 Quotes from each FF regarding the SCN degree

	Degree
MoS	**IQ9)** We work with specialty fabrics, so mills are very important to us as well. And we have direct relationships with that tier of supplier, essentially. **IQ9)** So the first one is tier ones we actually have a set of... They're a type of middle men essentially, most apparel factories that I'm aware of essentially go through these middlemen. **IQ12)** Again, it depends which one. I would say we have probably right now 40% ish, maybe a little more, maybe closer to 50% of our line with one specific [Tier 1] supplier.
ProtoJet	**IQ9)** So that would make us more of a tier two …we're pretty much more of a black box.. company …people come to us and they give us drawings, prints, data, and say, "Hey, will you make this?" And then we'll make it for them. **IQ9)** I'm saying most of the materials that we get from our suppliers is raw material, since we're not sending out different sources.
Xometry	**IQ7)** And as [suppliers] start, we do a crawl, then walk, then run. So they're able to first take one job at a lower revenue value and get that done. And that helps them understand how the site works, how to navigate our digital tracking tools, print out packing slips and do everything through our digital platform. **IQ7)** like the GEs of the world, they're all around like, "How big is your shop? Who's your QA manager?" And all these things, and that are basic, very myopic on a single shop with the single shop capabilities. And we're like, "We're everything."

Closeness centrality, closely related to the clustering coefficient when discussing network efficiency, is challenging to measure for non-FFs without each firms' specific relational data. Mainly developed to understand network clustering, IQ10 attempted to comprehend non-FF interrelationships, and the answers partly contributed to the understanding of closeness centrality. **Table 3.7** examines each FF's closeness centrality through quotes regarding redundancy. MoS states that its network does not have Tier 1 supplier redundancy; however, their direct connections to their Tier 2s and 3s were considered. ProtoJet does not have much supplier redundancy, especially with specialized raw materials. Still, its path length is less of a critical efficiency factor since they are directly linked to raw material suppliers. Similar to ProtoJet, Xometry has a mass number of directly connected suppliers, providing considerable redundancy.

Table 3.7 Quotes from each FF regarding the SCN closeness centrality

	Closeness Centrality
MoS	**IQ8)** We have one or two products where there is redundancy, but this is actually an issue that we've run into, we don't have a ton of redundancy. **IQ9)** …That would be how we expand outwards in the tier section that you're talking about. Having said that, we have direct relationships with several people in the factories themselves and we also have direct relationships with mills.
ProtoJet	**IQ8)** I think that there is a backup plan, but I don't know if it's like multiple sources. That may be true in many other businesses, but in ours it's a little bit more specialized …We don't have quite a backup as maybe a lot of other places have, but [we] always have to have a plan B in mind, but it's not like there's a lot of redundancy.
Xometry	**IQ7)** …between 2020 and now, there have been no disruptions to our customers for domestic work, even with the pandemic, because we have so many geographically dispersed suppliers and redundancy per technology offering. **IQ7)** …we have multiple redundant suppliers that are able to review a potential fit.

Table 3.8 examines network clustering, or more specifically, relationships between other non-FF nodes that form triads. MoS has large Tier 2s that crossover between other Tier 2s and Tier 1s, signifying network transivity. Also, while less likely, Tier 3s occasionally purchase raw materials from each other during shortages (Lazzarini et al., 2001). Therefore, since ProtoJet contracts with primarily raw material suppliers,

their network is likely to include the presence of triads. ProtoJet described the likelihood of competitive relationships between their Tier 3 suppliers, further demonstrating those non-FF links. Finally, Xometry provides forums for their suppliers to connect, but it is not clear the extent to which firms form relationships. From Xometry's perspective, their suppliers do not need each other to produce parts.

Table 3.8 Quotes from each FF regarding the SCN clustering coefficient

	Clustering Coefficient
MoS	**IQ11)** One of our manufacturers, I will mention, for dress shirts does make about, I think they said, one out of five at one point dress shirts in the world and so there are 100%, we definitely use a factory that [has crossover]
ProtoJet	**IQ10)** So do they collaborate? Yes, but it would be an unwritten rule or process as to how they do that … So I know for sure some places will benchmark and call another place and say, "Hey, do you have any of this material in house?" And they'll be like, "No," so they'll know, "Hey, it's low supply right now, so let's increase the pricing." **IQ11)** *do [competitors] use the same suppliers as you do?* Yeah, a lot of them do.
Xometry	**IQ10)** We do have a manufacturing community with forums where people can create topics and discuss around that. And we really encourage our manufacturers to participate in the community because the best way to say it is, it is like being in the trenches together.

Table 3.9 contains the responses from each interviewee after analyzing IQ16's scale-free and small-world networks. MoS identified its network as scale-free, citing that part of the topology represented their upstream suppliers. This answer relates to its material flows but does not consider their relationships with Tier 2s and 3s. ProtoJet selected the small-world topology since their consumer-type varies greatly, and their suppliers fluctuate to meet that demand. However, their suppliers are all Tier 3s, so the upstream link complexity is limited. Xometry selected small-world, concisely stating that each node was connected through the Xometry platform. From the consumers'

perspective, however, all suppliers connect to Xometry, but do not necessarily have direct links to one another. For example, a supplier would not reach out to another supplier if they went down, they would reach out to Xometry which could then communicate with another supplier (more scale-free than small world).

Table 3.9 FF network type identification and explanatory quote

	Self-Identified Network Type	Explanation
MoS	Scale-free	I answered that specifically to that is upstream, but if we're talking downstream as well, then basically what I answered was that is upstream and then everything else coming out from me is downstream. Yeah, that one [bottom-left] branch would've been upstream, essentially going in and then everything else would be downstream.
ProtoJet	Small-world	I think because of the nature of our business and our clientele, with it being maybe, say, 60% automotive and 30% medical and commercial, and then 10% mix up for ...Because of that we are hitting a bunch of different suppliers a lot of times.
Xometry	Small-world	Although Xometry is the platform, everybody's running the app. So it is very much the Uber versus dispatcher approach.

The researcher extracted information from the transcripts and created the links with a Python script for each FF; a combined script is available in **Appendix E**. A $G_{n,m}$ random graph is generated with the same n nodes and m links as its corresponding MPP network, serving as a benchmark. Since random networks lack structure leading to low clustering, a real-world SCN should perform better than a random network.

CHAPTER 4

RESULTS

4.1 MPP SCN Topology

The three interviewed MPP FFs, displayed in **Table 4.1**, varied in SCN size, industry, and business model. For example, while both ProtoJet and Xometry create parts for prototyping, ProtoJet manufacturers their parts while Xometry subcontracts the manufacturing to capable manufacturer(s). Consequently, due to supplier and distribution connection differences, the resulting topologies were very diverse. The following subsections detail the individual networks and compare their topology degree distribution to determine the network type. The network metrics between topologies cannot be compared due to differences in network size, so a random network is generated for each topology with the equivalent quantity of nodes and links.

Table 4.1 Detailed MPP Firm information

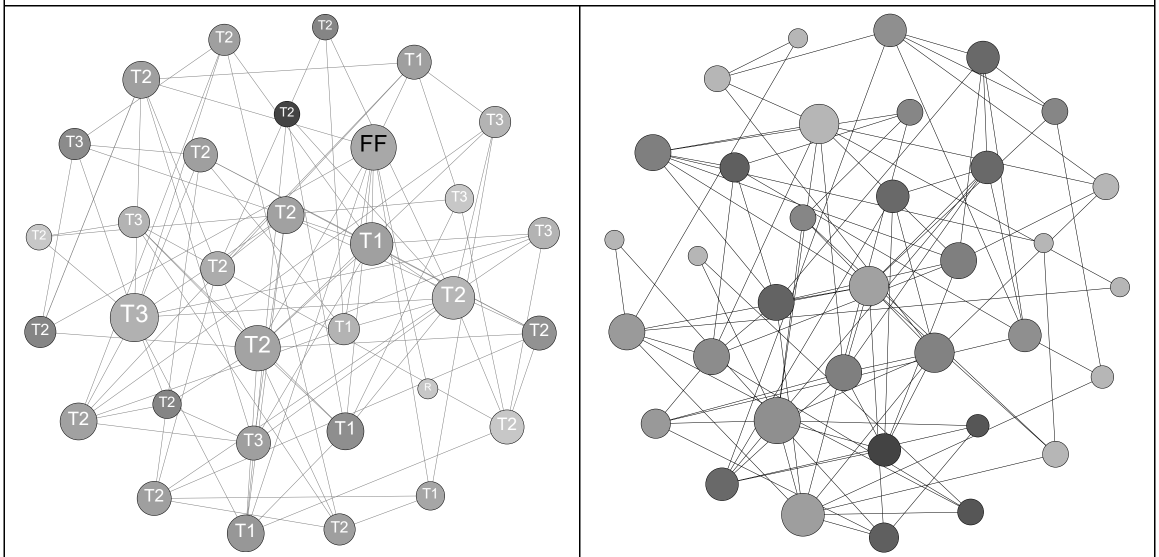
Firm Name	SCN Size (Max)	Industry	Business Model
MoS	36	Apparel	Mixed Manufacturing
ProtoJet	67	Prototyping/Production	On-Demand Manufacturing
Xometry	5006	Prototyping/Production	On-Demand Platform

4.1.1 Network Type

MoS's topology, presented on the left side of **Figure 4.1**, is a relatively small SCN with only 32 firm nodes. The size of each node corresponds to its degree, with the FF and a few Tier 1s & 2s having a slightly higher number of links than the rest. The shade of the node relates to its clustering coefficient; for instance, a node that is a part of a triad, where three nodes are connected to one another, will have a coefficient of 1 and be colored black. Nodes that are dark and large are considered crucial to the network. For MoS's topology, most nodes are a light-to-medium shade of grey, with a single, small node that is black. The network degree average of 5.875 and the clustering coefficient of 0.192 indicate an overall large quantity of connections and clustering between nodes. Compared to its random graph counterpart, shown on the right side of Figure 4.1, the SCN has a high clustering coefficient and lower closeness centrality, demonstrating a real-world topology.

Node-level Clustering Coefficient

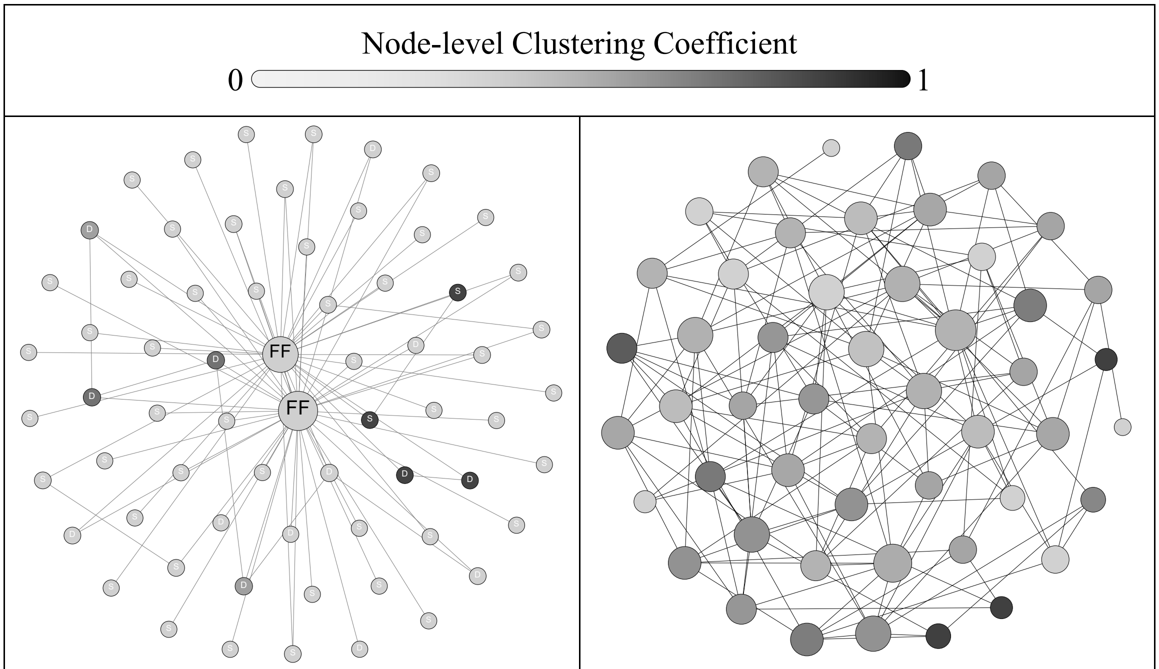
0 — 1



Ministry of Supply	Random
# of Nodes: 32	# of Nodes: 32
# of Links: 94	# of Links: 94
Network Clustering Coefficient: 0.192	Network Clustering Coefficient: 0.147
Closeness Centrality: 2.066	Closeness Centrality: 2.269
Average Degree: 5.875	Average Degree: 5.314

Figure 4.1 MoS SCN with corresponding random network benchmark

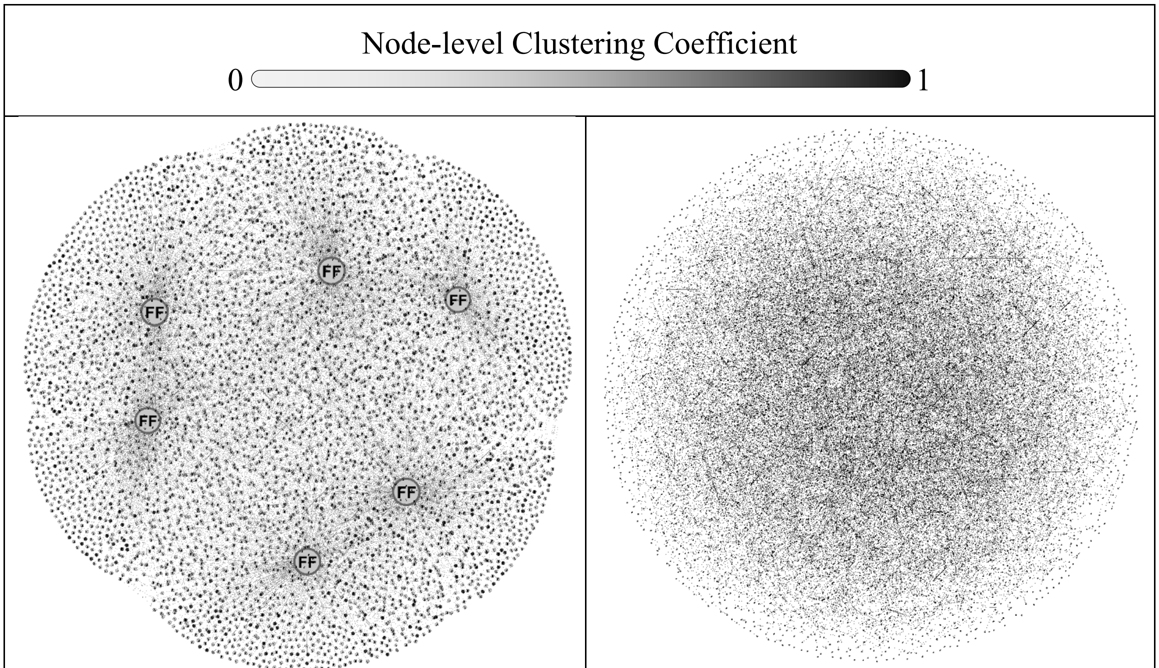
ProtoJet, while similar in size to MoS, is visually unique, as shown in **Figure 4.2**. The raw material supplier and distributor nodes are comparatively small, but a few of the nodes are linked together, forming a slightly higher degree and node-level clustering coefficient. The FF nodes are much more prominent because they are connected to all the suppliers and distributors. Compared to its random counterpart, the ProtoJet SCN has a much higher network clustering coefficient at 0.24 since any non-FF connection forms a triad with the FFs. However, the lack of non-FF triads results in a higher closeness centrality than the random network, indicating inefficiencies from longer path lengths.



ProtoJet	Random
# of Nodes: 66	# of Nodes: 66
# of Links: 83	# of Links: 83
Network Clustering Coefficient: 0.24	Network Clustering Coefficient: 0.107
Closeness Centrality: 2.561	Closeness Centrality: 2.382
Average Degree: 2.515	Average Degree: 5.92

Figure 4.2 ProtoJet SCN with corresponding random network benchmark

Xometry's network is orders of magnitude larger than the previous two FFs, and the visualization from **Figure 4.3** demonstrates a clear degree difference between Xometry and its suppliers. Since Xometry stated that their suppliers might collaborate, a minuscule probability was added to simulate this possibility, and with every supplier connecting to Xometry, any link between suppliers results in a triad. There are 5000 possible links per node; even with a small probability, this results in a relatively large clustering coefficient at 0.154. This coefficient contrasts the random network, which essentially has a non-existent possibility that three nodes connect with each other. Xometry's triads also create a smaller closeness centrality of 3.87 with more pathways to get between nodes. Surprisingly, the average degree between networks was the same at 2.987. While Xometry's suppliers were typically not linked to each other, the average random node had at least one connection to another node. This, along with Xometry's six hub nodes' immense number of links, caused the two network degrees to converge.



Xometry	Random
# of Nodes: 5006	# of Nodes: 5006
# of Links: 7477	# of Links: 7477
Network Clustering Coefficient: 0.154	Network Clustering Coefficient: 0
Closeness Centrality: 3.87	Closeness Centrality: 7.781
Average Degree: 2.987	Average Degree: 2.987

Figure 4.3 Xometry SCN with corresponding random network benchmark

Whereas the individual network characteristics illuminate potential SCN patterns, the degree distribution, displayed in **Figure 4.4**, provides a straightforward, visual method to classify each network as scale-free or small-world and compare the networks for similarities. MoS approximately demonstrates the Poisson distribution characteristic of small-world networks. Its high clustering and low closeness centrality further validate this finding. ProtoJet differs significantly in its distribution; the logarithmic trendline resembles a power-law degree distribution, a classic characteristic of scale-free presence. This distribution and the observation that most network links connect to the FF provide evidence that the network is scale-free.

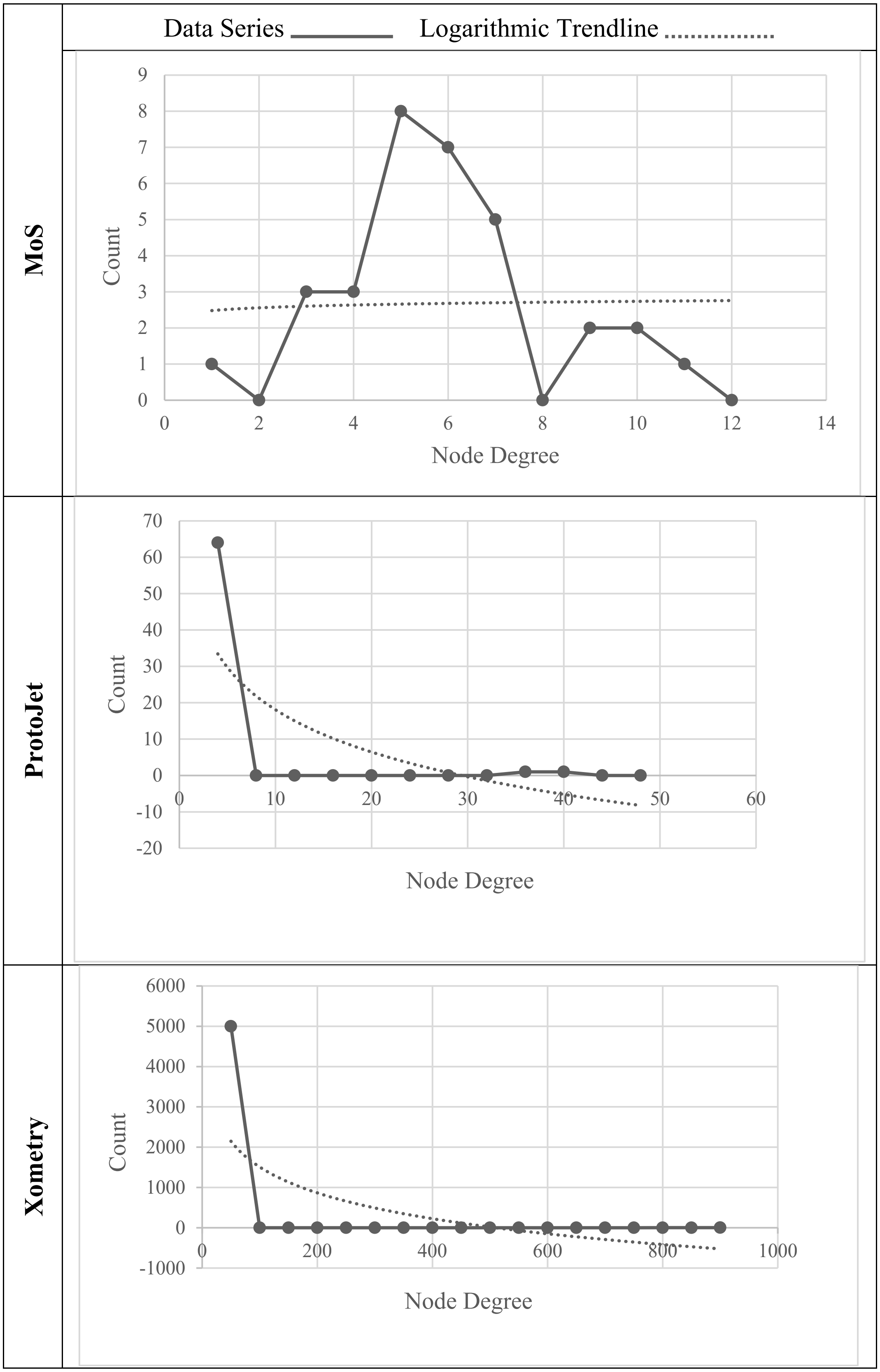


Figure 4.4 Degree distribution of the three FF SCNs

Though a much larger network, Xometry has a similar power-law trendline as ProtoJet, and **Figure 4.3** demonstrates the presence of hub nodes by the FFs. For these reasons, Xometry has a scale-free network. While Xometry and ProtoJet are scale-free, there is not enough evidence to generalize all MPP networks as scale-free. Instead, the firm type and placement within the SCN is the ultimate contributor to network type; this topic is explored further in Chapter 5. The following section delivers the final codes and resulting themes.

4.2 Themes

The background theme contained codes pertinent to the interviewee's expertise and FF type, but it was not considered a final theme since the information was irrelevant to the research questions. The SCN and disruption groups were essential to answering RQ1 and RQ2, respectively, so they were categorized as final themes.

4.2.1 Theme 1: Supply Chain Network

The SCN theme consisted of 15 codes relevant to the topology of the FF SCNs. The theme was divided into five groups, each with its applicable codes. **Figure 4.5** shows the theme along with each group, with slight modifications to specific code names for clarity.

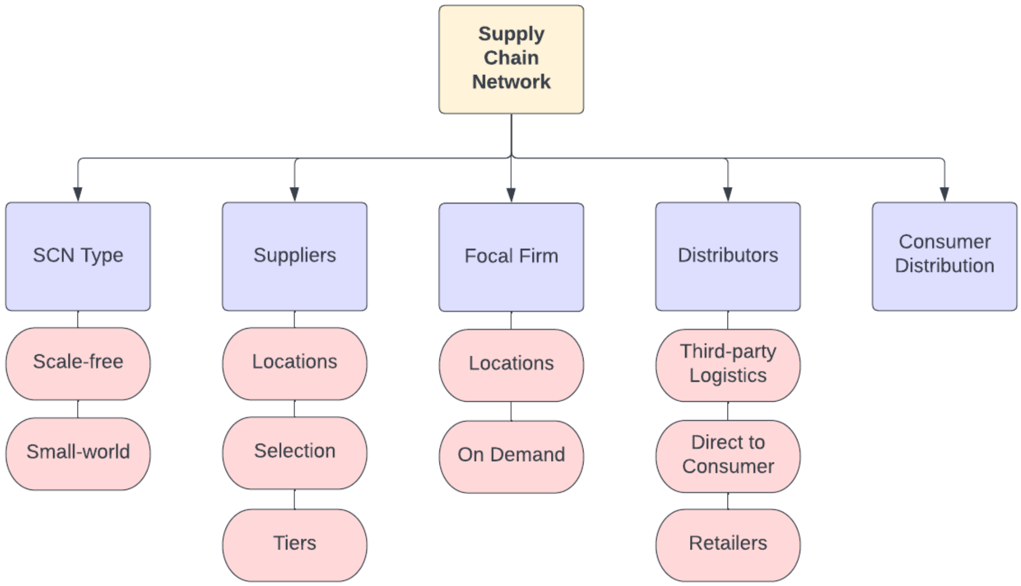


Figure 4.5 SCN theme with five categories and relevant codes

SCN Type (coded as SCN) were quotes from IQ16 relating to the interviewee's perception of their network, with scale-free and small-world codes for specific explanations of their network. The supplier group contained quotations for selecting new suppliers, supplier geographical distribution and quantity, and supplier tiers. A few supplier location quotes were double-coded with disruption-related themes since firm location is pivotal in SCN robustness. For example, the following quote was double-coded for robustness and supplier locations.

"…we resourced our products to new factories and we were looking at factories all over Asia. So we actually resourced a lot of our stuff. So majority prior to 2020 were all in China and Taiwan. We now have manufacturers that we make in China, Taiwan, Indonesia, Vietnam. So we went all over Asia and Thailand, which is really, really helpful

because in one Chinese city... Sorry, in China, they would get a COVID spike, but in Indonesia they'd be okay for another two weeks and then all of a sudden it would like flip."-**MoS**

Geographically dispersed suppliers helped MoS avoid downtime during the initial COVID-19 spike, demonstrating robustness. The focal firm group contained location and on-demand codes; an on-demand code, exemplified in the quotes below, were statements related to the FFs production method. This code was crucial in identifying the FFs role within its SCN.

"I'm thinking because we're not necessarily design responsible, maybe. So we're not the one coming up with the idea of what we're selling. You know, we're pretty much more of a black box, maybe, company. In other words, people come to us and they give us drawings, prints, data, and say, "Hey, will you make this?" And then we'll make it for them."-**ProtoJet**

"*There's very rare occasions where we have contract manufacturing work where we're also doing whole kit and caboodle, full out package goods and stuff like that. So we have some of that work, but a lot of our work is what I would call on-demand custom. So it's custom manufacturing components, whatever process, whatever quantity they want."*

-Xometry

The distributors group consisted of codes concerning the FFs downstream relationships. FFs using third-party logistics (3PL) outsource the distribution of final products. The direct-to-consumer code included quotes concerning business-to-consumer (B2C) and business-to-business (B2B) distribution. MoS mentioned 3PL, B2C, and a single retailer as their distribution methods, and all three FFs stated that B2C was a distribution method. ProtoJet and Xometry also distributed products business to business (B2B).

"So it would be we're doing direct to consumer, e-commerce and we have one retail outlet."-**MoS**

"A lot of our work is either B2C or B2B. Most of our customers are B2B, so it'll be like a GE or a NASA who is asking for a part to be manufactured. They go to our site, specify it, press order and then we fulfill the part to deliver it to them. So they're the ones that are creating it as an inventory item, if that makes sense. So we're their manufacturing partner and they're more the people that are doing their distribution on that side."-**Xometry**

The final group, consumer distribution, held quotes relating to consumer location and type. All three firms had a global distribution of consumers. Though consumer nodes were not added to the proxy networks, their distribution demonstrates the extent of FFs geographical presence and how disruptions might impact different groups of consumers.

4.2.2 Theme 2: Disruptions

The disruption theme consisted of ten codes divided into four categories, displayed in **Figure 4.6**, pertinent to answering RQ2. Two categories, disruption origin and disruption effect, provided evidence of disruption cause and effect. The other two categories, robustness and resilience, contained codes regarding how the firms resisted and, if applicable, recovered from the aforementioned disruptions.

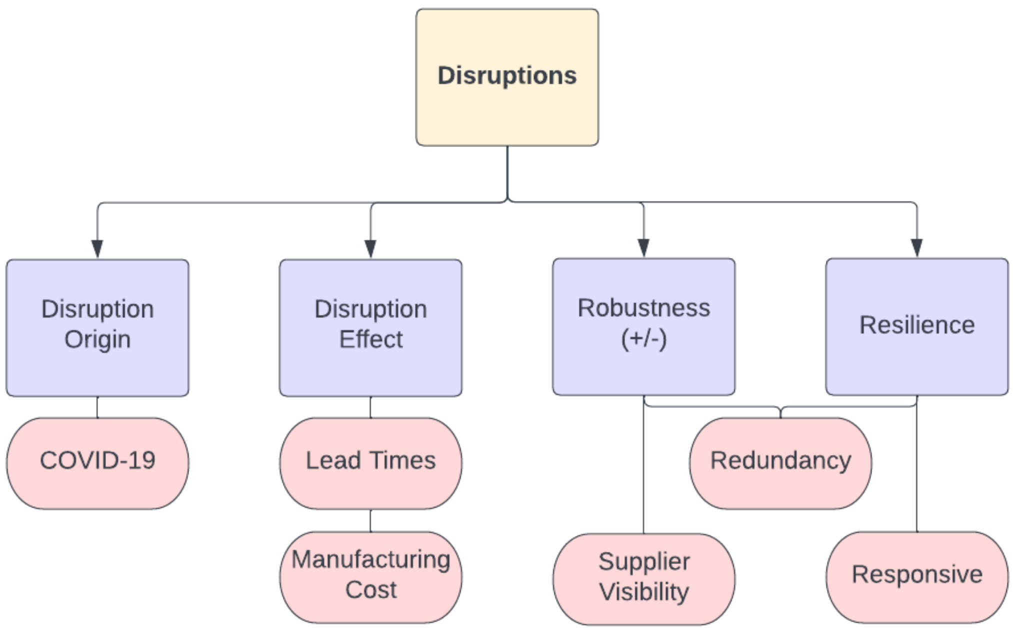


Figure 4.6 Disruptions theme with four categories and relevant codes

The disruption origin group contained quotes referencing the disruption type, time frame, or initial origin. COVID-19 was cited as a disruption multiple times, so it was given its own code. Most COVID-19 quotes were double-coded with disruption effect codes; examples are provided in the next paragraph. Xometry also mentioned that insufficient consumer technical files lead to downtime, an interesting MPP-related internal disruption. Without this technical data, Xometry could not connect the consumer to a manufacturer, creating a supply chain bottleneck.

"I'm saying that because one of the biggest challenges in supply chain disruption is not who my supplier is. It is, but for us it isn't. It's the technical data. The technical information. Do you have your technical information for the parts that you own up to date to a point where you can give it to another [manufacturer] and they can make it? And that was the big gap in this disruption was that the ownership of that technical information. So a lot of it was held by the probably tribal knowledge by the supplier who's been making it for the last decade, and all of a sudden they're shut down and you're starting from square one. And for me personally, that was the biggest disruption I saw, was the fact that we had so much capability and so much capacity, we could do so much, and you're just waiting for someone to give you the technical files."-**Xometry**

The disruption effects group consisted of quotes relating to the specific interruptions encountered by each FF. The most substantial disturbances experienced were amplified manufacturing costs and lead times, especially from COVID-19. Disruptions caused supply shortages, sharply increasing demand and therefore manufacturing prices.

"COVID-19 is still getting us honestly through materials costing. I think that would be the biggest impact that we're really seeing right now."-**MoS**

"…we had a lot of [COVID] restrictions in trying to get materials, and then material companies out there are jacking their prices big time up, probably to offset the supply and demand, obviously, but it's also taking advantage of the situation too. And we've had to pass that on to our customers…"-**ProtoJet**

Xometry did not mention any issues relating to increased manufacturing prices. Still, COVID's far-reaching pricing effects are expected to affect Xometry's suppliers. MoS stated that an upstream disruption would cause significant increases in supply lead time since their product offering is sourced chiefly from specialty suppliers. While they avoided this interruption during COVID, MoS encountered increased lead times downstream. Consumers likely experienced longer wait times, detrimental to retention and satisfaction. Since they contract with multiple standard raw material suppliers, ProtoJet did not experience increased lead times due to supplier shortages, rather, the COVID lockdowns limited their ability to produce and deliver parts.

"But in terms of lead time …I was mentioning that it takes a long lead to switch factories. So in terms of lead time, I would say 150 to 200 days to get some of those items, regardless of the factory, back up into a totally new [supplier]"-**MoS**

"Yeah, so I would say that COVID-19 really affected us with shipping lead times, mostly from shipping internationally, so freight forwarding"-**MoS**

"… for us it wasn't quite as bad because of how small we were, and since we only had 15, 20 people in the shop, each one was somewhat isolated around the plant, so we weren't working hand to hand with a lot of stuff. …but it did affect our abilities to move around. Like some of the plants that we were shipping parts to were closed, you know? Or had only certain windows of time that you can drop parts off and come back with them."-**ProtoJet**

While they experienced manufacturing bottlenecks during the company's first year, Xometry stated that they did not experience any increase in consumer lead times during the pandemic.

"…I'll put it bluntly, between 2020 and now, there have been no disruptions to our customers for domestic work, even with the pandemic, because we have so many geographically dispersed suppliers and redundancy per technology offering."-**Xometry**

The robustness group contains quotes regarding each FFs ability, or lack thereof, to resist disruptions. Redundancy, a key contributor to robustness and resilience, was considered robustness-related if it affected the firm's ability to resist downtime. MoS, for instance, discussed that their lack of redundancy was caused by their specialty goods and the time required to switch to a new supplier of equivalent quality. ProtoJet had a similar issue with redundancy; their specialization made it challenging to find multiple suppliers capable of fulfilling their needs. Given their platform design, Xometry always has multiple potential suppliers ready to fulfill an order, so redundancy is not an issue.

"We have one or two products where there is redundancy, but this is actually an issue that we've run into, we don't have a ton of redundancy."-**MoS**

"So I think that there is a backup plan, but I don't know if it's like multiple sources. That may be true in many other businesses, but in ours it's a little bit more specialized …We don't have quite a backup as maybe a lot of other places have, but we definitely always have to have a plan B in mind, but it's not like there's a lot of redundancy."-**ProtoJet**

"…that comes down to, we have multiple redundant suppliers that are able to review a potential fit. So here's a job, here's my suppliers lined up. A supplier can review and say, "Hey, I don't want to take that." And I'll automatically go to the next supplier. And multiple suppliers will start to see this work, and typically, one takes it."-**Xometry**

Firms with increased supplier visibility can see an impending disruption and make necessary changes before an interruption occurs, demonstrating robustness. MoS had relationships with all three tiers, indicating increased visibility. However, their visibility is limited to Tier 2; MoS cited their Tier 3s as unwilling to disclose the source of disruption beyond stating that there was a yarn shortage. ProtoJet had direct links to raw material suppliers, so though they could clearly see imminent disruptions, their proximity to the Tier 3s prevented quick adjustments. Xometry had so many links to suppliers that they could create a macro-level dynamic map of disruption events to predict interruption propagation and adjust accordingly. This level of visibility was pivotal in preventing interruptions during COVID-19 and the California wildfires.

"Having said that, we have direct relationships with several people in the factories themselves and we also have direct relationships with mills. We work with specialty fabrics, so mills are very important to us as well. And we have direct relationships with that tier of supplier, essentially."-**MoS**

"…we can get to the fabric level, but I can't hear if there's a shortage of yarn. All I know is there's a shortage of polyester yarn to make our fabrics. I don't know, for example, why there's a shortage of yarn or what the backups are in those factories."-**MoS**

"…that gives us what happens in a macro level is you see our supply chain's very elastic. You can see there's clusters where you see regular work, but say out in California, there's forest fires, you'll see that move over to Utah or Maryland or in Northeast, or essentially US. But you'll see the work naturally move around. …We also do have a crisis center. So we also track the weather patterns and the major events. So we try to do proactive work. So if we see any potential disruptions, we notify those areas and usually we're very good at working around there."-**Xometry**

The resilience group contained codes related to how the firms responded to interruptions; many quotes provided specific examples. For instance, ProtoJet had to modify its business model to produce masks during COVID.

"when COVID hit, then we had to ... We still had to knock on some windows and doors to find more business, and it was tougher. It was tougher to find the business because people were freezing up, they weren't necessarily releasing jobs"-**ProtoJet**

Redundancy, regarding resilience, impacts the number of options a firm has to return to normal operations. MoS cited an extended amount of time would be needed to recover after an interruption due to their lack of redundancy.

"We use a totally different tier one supplier. So if our tier one supplier went out, it would take 150 to 200 days to make 100% certain that we are doing it at 100% quality."-**MoS**

The most significant indicator of sufficient resilience is the FF's responsiveness when disrupted. MoS responded quickly to COVID-induced supply shortages by iterating over their entire line. While less responsive, ProtoJet was able to modify its manufacturing processes to create masks during downtimes. Anytime Xometry experiences an interruption, they can switch to an unaffected supplier.

"Everything shut down in March, mid-March we were already immediately like, "Okay, how do we reset? ...I think we actually may have jumped on it faster than a lot of our competitors in terms of pivoting some of our stuff. And so our factories and partners were really responsive and were able to jump on those changes pretty quickly, and we were able to get some of those normal lead times."-**MoS**

"'Oh, we'll make face masks,' you know? And so we were being creative in how to create work."-**ProtoJet**

"Xometry on the supply chain side is extremely resilient, extremely resilient. Usually the disruptions to projects come from either a customer where there's a change of scope in the project, while you're well into production and something needs to change."-**Xometry**

The disruption theme helps the researcher analyze how the topology relates to each FF's robustness and resilience. This analysis, available in the Chapter 5, examines the strengths and weaknesses of MPP SCNs.

4.3 Code Scheme

The 26 final codes fell into three groups, with two groups considered main themes. Since the interview was well-defined, the themes developed naturally and reflected the original research questions, but within each theme, interesting codes emerged relating to disruptions and MPP SCNs. The subsequent subsections discuss these codes and their relationship to the themes.

4.3.1 Code Frequency

Table 4.2 shows the frequency of final codes within their parent themes. Section 4.3 will interpret each code, but by observing the total for each group, patterns develop pertaining to specific codes. For example, interviewees mentioned lead time on 8 separate occasions when discussing disruptions, indicating a probable correlation. However, final codes cited once or twice are also significant since they could not be merged with another section or excluded due to irrelevance. SCN, for instance, was coded once, but the related quote was essential to creating the proxy networks.

Table 4.2 Code frequency table

	Codebook	Totals	Percentage
Background	Competitors	4	3.6%
	Interviewee Experience	4	3.6%
Disruptions	COVID-19	7	6.3%
	Lead times	8	7.2%
	Manufacturing Cost	3	2.7%
	Disruption Effect	1	0.9%
	Disruption Origin	3	2.7%
	Resilience	6	5.4%
	Resilience Responsive	2	1.8%
	Robustness (+/-)	6	5.4%
	Redundancy	7	6.3%
	Supplier Visibility	10	9.0%
Supply Chain Network	SCN	1	0.9%
	Scale-free	1	0.9%
	Small-world	2	1.8%
	Suppliers	4	3.6%
	Supplier Locations	6	5.4%
	Supplier Selection	5	4.5%
	Supplier Tiers	4	3.6%
	Focal Firm	5	4.5%
	Focal Firm Locations	4	3.6%
	Focal Firm On-demand	2	1.8%
	Distributors	5	4.5%
	Distributors 3PL	1	0.9%
	Distributors D2C	5	4.5%
	Distributors Retailers	1	0.9%
	Consumer	4	3.6%

4.3.2 Interrater Reliability

The interrater reliability method was adopted to measure the coding scheme's reliability.

Exhibited in **Table 4.3**, a coding confusion matrix was created to display the exact proportions of agreement/disagreement. If there was perfect agreement between coders, the red off-diagonal values would be equal to zero.

Table 4.3 Coding confusion matrix

		Coder 1: Yes	Coder 1: No	Totals
Coder 2	Yes	26	2	28
	No	2	15	17
	Totals	28	17	45

Overall, there was little disagreement on codes; Cohen's Kappa and the percentage agreement in **Table 4.4** justify this sentiment. The Kappa value accounted for the chance of agreement and was calculated to be 0.88, which is considered "almost perfect" agreement (Viera & Garrett, 2005). The percentage agreement further validates this with a 91.11% agreement.

Table 4.4 Reliability values

Method	Cohen's Kappa	Percentage Agreement
Value	0.88	91.11%

This Kappa value would be considered very high for many coding schemes. However, the research and interviews questions were well-defined, and the coding scheme went through multiple iterations, with an initial code adjustment between coders. Thus, the high Kappa value demonstrates the culmination of numerous reliability steps.

CHAPTER 5

DISCUSSION

5.1 Network Structure

The results from 4.1 identify MoS, ProtoJet, and Xometry as small-world, scale-free and scale-free topologies, respectively. Therefore, there is sufficient evidence that all MPP firms do not all share a specific network type. Instead, as observed from the results, the network type is determined by the FF's role and centrality in relation to other firms. Suppose the FF acts as a Tier 2 and deals directly with raw material Tier 3 suppliers, like ProtoJet. In that case, there is less potential for collaboration/clustering than exists for a FF with Tier 1,2, and 3 suppliers (e.g., MOS). Similarly, a firm's centrality within a network determines how other firms will link to it; a firm with a high degree of links will attract more connections, leading to a power-law degree distribution.

While the FFs do not all exhibit the same network type, certain SCN characteristics can be attributed to MPP. Downstream, all three FFs utilized B2C/B2B to get products to consumers without any retailers, except for MoS's single retail store that showcases non-MPP apparel. The lack of retailers demonstrates a shift towards on-demand purchasing and 3PL shipping. This business model prevents FFs from maintaining excess inventory, hiring retail workers, and purchasing retail space. Upstream, all three FFs had fluctuating, often specialized suppliers to satisfy the varying manufacturing demand for unique products. Section 5.2 discusses the impact of this fluctuation on an MPP firm's robustness and resilience

5.2 Impact of External Disruptions

Past SC network theory research has extensively investigated scale-free and small-world networks' response to disruption events. The following subsections will utilize this research to discuss how each MPP FF's network type corresponds to the firm's experienced robustness and resilience when faced with a disruption. This comparison will highlight specific MPP SCN characteristics that affect robustness and resilience.

5.2.1 Robustness

Network theory research has established that scale-free networks are more robust against random disruptions than small-world due to the hub node's increased supplier redundancy (Zhao et al., 2011). However, scale-free networks are more susceptible to targeted disruptions against the hub nodes, as each chain of connected supplier nodes would be severed by removing the hub node. Increased visibility is also necessary to decrease disruption propagation in both network types, aiding the FF's resistance to interruption (Basole & Bellamy, 2014).

Though affected by increased material cost, MoS's small-world SCN avoided a significant lead time interruption during COVD-19 due to a happenchance resource exercise that restructured their supply chain to incorporate multiple geographically dispersed suppliers; it is unclear if MoS's increased visibility with their Tier 2s and 3s was a factor in changing suppliers right before the pandemic started. Nevertheless, MoS cited lack of supplier redundancy as an ongoing issue and did have to partially reset when COVID hit. This interruption validates past research stating that small-world networks are susceptible to disruptions, especially considering MoS's lack of redundancy.

ProtoJet, though the hub node in their scale-free SCN, also lacked supplier redundancy and suffered downtime caused by COVID restrictions. ProtoJet's low supplier quantity can be attributed to requiring only a few, sometimes specialized raw material suppliers. Regardless of redundancy, the statewide restrictions affected the hub node, causing downtime for both ProtoJet and their suppliers; this corroborates past network theory research citing scale-free hub nodes as a potential weak point when disrupted, decreasing robustness.

Xometry's dispatcher approach to MPP is unique compared to the other two FFs and significantly contributes to the firm's scale-free robustness to random disruptions. Despite location-specific supply shortages or restrictions affecting a portion of suppliers, its consumer's product lead time did not change because of the sheer quantity of supplier redundancy. Xometry could see a disruption in real-time and make instantaneous changes when a disruption occurred with I4.0 technologies such as digital supply chains for tracking and artificial intelligence for automatic reselecting suppliers, demonstrating macro-level supplier visibility. Its redundancy and visibility were pivotal in preventing interruptions, validating scale-free's ability to avoid disruption.

5.2.2 Resilience

Network theory research has established that small-world networks are more responsive to and recover quicker from interruptions than scale-free networks (Basole & Bellamy, 2014). Whereas scale-free SCNs have more redundant suppliers who can significantly decrease downtime, small-world networks' high clustering and low closeness centrality efficiently transfer resources, leading to a quicker network-wide recovery (Nair & Vidal, 2011).

MoS's SCN serves as an example of small-world networks responsiveness. Though able to resist major interruptions due to geographical distance between suppliers during COVID, MoS still had to act quickly to change parts of their line affected by supply shortages and did so faster than their competitors, enabling standard lead times. They cited its relationship with Tier 1, 2, and 3 partners as the primary contributor to this responsiveness, validating past SCN research on resilience.

Despite the lack of supplier redundancy, ProtoJet's interruption was caused by statewide COVID restrictions, making it difficult to compare the impact of its scale-free topology to SCN research. Since many of the COVID supply shortages happened at the raw material level, ProtoJet would probably have been unable to quickly recover from a supply shortage. However, ProtoJet's flexibility during the interruption is worth noting, pivoting to manufacturing masks. This versatility is owed mainly to MPP technologies such as modular factories and configurable supply chains, allowing it to quickly switch to completely different materials and manufacturing tasks.

Xometry did have a few supplier disruptions during COVID, but its massive network of redundant suppliers was responsive enough to prevent changes in consumer lead time. Its proactive approach to detecting SCN disruptions through cyber-level weather prediction and disruption tracking assists in creating a resilient network.

5.3 Recommendations for MPP Firms

This research did not find SCN topological similarities between MPP firms; instead, it was observed that topology is formed by the FF's role and centrality. The network type does, though, reveal specific characteristics that affect its robustness and resilience. Understandably, SC managers cannot reasonably change their SCN structure without significant changes to the firm's role. However, MPP firms should leverage underlying evolutionary principles that make each network type robust or resilient.

To be robust, MPP firms should replicate the scale-free network's ample supplier redundancy to multiple resource streams, especially specialty suppliers (a commonly observed MPP trait). MoS highlighted the benefits of geographically dispersed suppliers, which is recommended for any global MPP SCN, by avoiding significant downtime during COVID. Further disruption resistance can be obtained by FFs increasing their upstream visibility through additional working relationships with indirect suppliers, as observed by Xometry's SCN. If financially feasible and logistically necessary, MPP firms should adopt similar proactive approaches to disruptions through advanced I4.0 capabilities like instantaneous event tracking and disruption prediction.

An MPP firm's resilience depends heavily on its role within the network; however, redundancy of important suppliers is crucial to recovering from an interruption. The responsiveness of the recovery is contingent on the entire network's health and ability to transfer resources efficiently. SCN research has shown that a large clustering coefficient, seen in small-world networks and exemplified by MoS, can respond quickly to an interruption due to the efficient network transitivity. To build triads into a network, MPP firms should contract with every supplier tier that collaborates openly with other suppliers. Lastly, MPP firms should take advantage of their inherent manufacturing configurability during a crisis and be willing to flex to producing in-demand products, similar to ProtoJet during COVID.

5.4 Addressing Proposed Research Questions

This research investigated two MPP-related SCN research questions. **Table 5.1** summarizes the findings for each research question.

Table 5.1 Summary of Research Questions and Findings

ID	Research Question	Findings
RQ1	What type of network topology most accurately represents a mass personalization supply chain network?	Evidence indicates that not all MPP firms have the same network type. There is also sufficient evidence that MPP firms distribute products B2C/B2B and that their supplier networks are flexible.
RQ2	How do disruptions impact MPP supply chain operations?	MPP firms with specialty, centralized suppliers are vulnerable to disruptions. MPP firms should implement redundant suppliers, network transitivity, and increased visibility to become robust against disruptions and resilient during interruptions.

5.5 Research Limitations

While a qualitative approach provided deep insights into each MPP SCN, there are limitations to this research that, while important, do not discount the significance of the research. First, this research utilizes network-based representations to model supply chains, which in itself does not fully represent supply chain networks as traditional network-based approaches are limited to existing network and graph theoretic-based metrics.

Further, this research interviewed three heterogeneous firms, and while this was sufficient to determine differences between firms, the research could benefit from additional data points. In addition to the data points, the data collected from the interviewees was limited to their respective knowledge, and other company employees should validate this data.

CHAPTER 6

CONCLUSION

MPP is a novel production method for firms seeking to efficiently produce unique product variations derived from the consumer's latent needs. These variations require connected, flexible manufacturing facilities and robust distribution systems, yet MPP research thus far has focused exclusively on the manufacturing environment. Using interview data from three MPP FFs, this work develops and compares three proxy SCNs to determine network type, finding evidence that not all MPP SCNs exhibit the same topology. Instead, an SCN type is influenced by the FF's role and centrality within a network. It was also observed that all three MPP FF's distributed products B2C/B2B and had flexible supplier networks.

Previous SCN research has characterized the SCN types and their expected robustness and resilience when encountering a disruption, citing redundancy, visibility, and responsiveness as significant factors. These findings are compared with each FF's disruption experience extracted from the interview data to validate the proxy networks and investigate MPP-related phenomena. It was discovered that MPP FFs are particularly vulnerable to disruptions when using non-redundant, centralized suppliers. However, FFs taking advantage of MPP technologies to increase visibility and supplier redundancy were robust to disruptions and quick to recover from interruptions.

6.1 Future Work

Building on the current research, future work could interview more MPP FFs to compare this work's findings and investigate other disruption events, specifically the impact of target disruptions on MPP SCNs. Another study might use the three proxy network topologies as a basis for agent-based modeling to test the impact of disruption scenarios and validate the findings of this study. The advantage of an agent-based approach is the ability to give each node and link specific attributes, such as initial node health or link weight, so a disruption simulation could accurately portray risk diffusion. The interview data contained rich insights into the FF's SCN and their specific production methods. For example, Xometry experienced significant issues with the consumer technical files, an internal disruption. While this study focused on the MPP SCNs and external disruptions, future studies could utilize these details to examine what MPP technologies make the FFs robust internally.

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APPENDICES

APPENDIX A: Initial Interview-Research Questions Matrix

<table>
<tr><td colspan="7">My name is Bryce Schuebert. I’m an engineering research assistant at the University of Georgia, and I’m investigating a production method called mass personalization (MPP), which allows the consumer to be a part of the design process. I identified COMPANY NAME as a MPP company due to {insert how the company uses MPP}. I am researching what type of technology and supply chain configuration makes this possible and resilient to disruptions. This research aims to understand how well your product's supply chain holds up against various disruptions such as COVID-19. To do this, I need to computationally build a proxy supply chain network (SCN) topology based on your company's (and a few other MPP companies) unique production model. My findings will identify MPP SCN commonalities, which can provide a deeper understanding of the strengths and weaknesses of the supply chain. Would you be willing to participate in an interview lasting approximately 30 minutes?

If yes: Thank you! Would you consent to an audio recording of our conversation and the use of your name/companies name in my thesis?
➔ If yes: Great, please let me know if you’d like to turn off the recorder or keep something you said off the record.
➔ If no: I understand. I will only take notes of our conversation and/or will leave the company name out.
If no: Thank you for your time!

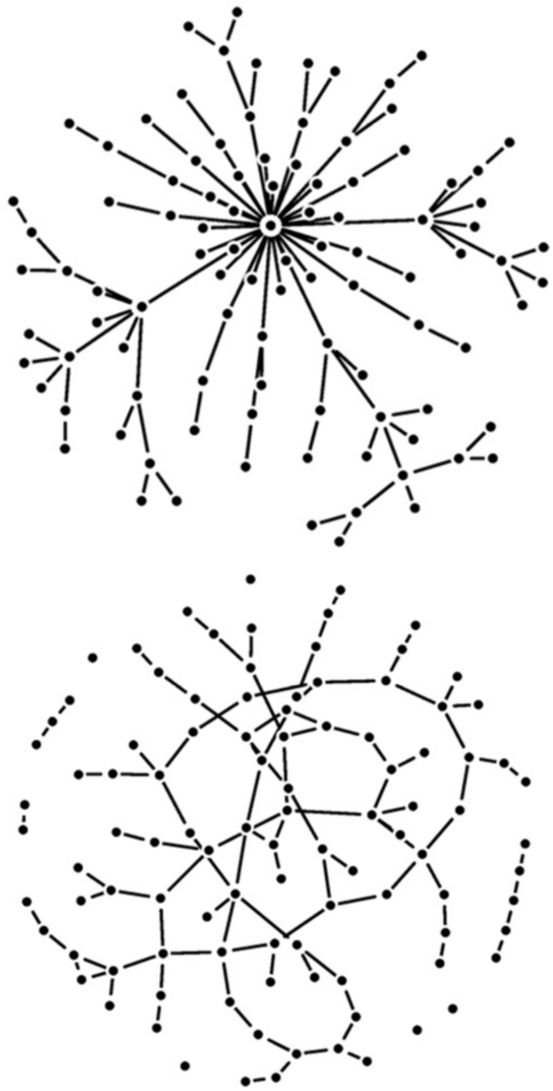
Before we begin, do you have any questions? [Discuss questions]
Please feel free to stop and ask any questions; I would be more than happy to answer your questions.</td></tr>
<tr><td colspan="7">Begin Semi-structured Interview</td></tr>
<tr><td>RQ1: What type of network topology most accurately represents a mass personalization supply chain network?

RQ2: How does the network topology impact supply chain functionality?</td><td>Background Information</td><td>SCN Makeup</td><td>SCN Selection</td><td>Robustness
---
withstand a disruption’s impacts</td><td>Resilience
---
restore functionality after disruption</td><td>Disruptions
---
node or network-level</td></tr>
<tr><td colspan="7">Interviewee Introduction
I’d like to start by asking you a few general questions.</td></tr>
</table>

IQ1. How long have you been with *COMPANY NAME*	X					
IQ2. What is your current role within *COMPANY NAME*	X					
IQ3. Who is your primary competitor?	X		X			
***COMPANY's* SCN Structure** *Thank you for sharing information about your background. I'd like to transition to talking about how COMPANY supply chain network.*						
IQ4. How large is your SCN?		X				
IQ5. How many tiers deep is your supplier network?		X				
IQ6. How many manufacturing plants are in your network? Are they all *COMPANY NAME*?		X				
IQ7. How do consumers receive finished products? Straight to consumer, through a distributor, from a retailer, hybrid, etc. *Follow up if dist. or retailer exists:* How many distributors and/or retailers are in your network?		X				
IQ8. Are there specific preferences when choosing a new/replacement supplier? *Probe: location, etc* *Preferential attachment*			X			
IQ9. Do you have redundancy in your network?		X	X	X		

Buffer						
IQ10. How much do your suppliers talk to one another? *Clustering*		X		X		
IQ11. Do your competitors use the same suppliers?			X		X	
IQ12. How quickly could you recover if a supplier were to go OOB overnight?					X	
Disruptions *Thank you for sharing information about COMPANY's supply chain. I'd like to transition to talking about COMPANY's history of overcoming disruptions such as COVID-19*						
IQ13. What types of disruptions have you experienced in the past?						X
IQ14. Please tell me about an example of an "easy" disruption that is quick to recover from. Why is it easy? *Follow up*: Same, but hard					X	X
IQ15. In those examples, did you know the origin of the disruption? *Visibility* *Follow up*: Where (upstream/downstre am)				X	X	X
IQ16. Do you think the makeup of your supply chain network impacts how quickly you can recover from a disruption?		X			X	X
IQ17. Please give me an example of a				X		X

supply chain-wide disruption that you experienced *Use covid here as an example* *Follow up*: How did you recover?						
IQ18. Given your experiences with disruptions now, what do you think your SCN should look like? *Show picture of scale-free and small-world networks*		X				X



(Airoldi et al., 2011)

Initial matrix of interview questions against research questions (Adapted from Castillo-Montoya, 2016)

APPENDIX B: Activity Checklist for Interview Protocol

Aspects of an Interview Protocol	Yes	No	Feedback for Improvement
Interview Protocol Structure			
Beginning questions are factual in nature	✓		
Key questions are majority of the questions and are placed between beginning and ending questions	✓		
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments	✓		
A brief script throughout the interview protocol provides smooth transitions between topic areas	✓		
Interviewer closes with expressed gratitude and any intents to stay connected or follow up			
Overall, interview is organized to promote conversational flow	✓		
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)	✓		
Only one question is asked at a time	✓		
Most questions ask participants to describe experiences and feelings			
Questions are mostly open ended	✓		
Questions are written in a non-judgmental manner	✓		
Length of Interview Protocol			
All questions are needed	✓		
Questions/statements are concise			Some questions takes time understanding (research/academic level)
Comprehension			
Questions/statements are devoid of academic language	✓		
Questions/statements are easy to understand	✓		

Aspects of an Interview Protocol	**Yes**	**No**	**Feedback for Improvement**
Interview Protocol Structure			
Beginning questions are factual in nature	√		
Key questions are majority of the questions and are placed between beginning and ending questions	√		
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments			
A brief script throughout the interview protocol provides smooth transitions between topic areas	√		
Interviewer closes with expressed gratitude and any intents to stay connected or follow up			
Overall, interview is organized to promote conversational flow	√		
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)			
Only one question is asked at a time	√		
Most questions ask participants to describe experiences and feelings			
Questions are mostly open ended			
Questions are written in a non-judgmental manner	√		
Length of Interview Protocol			
All questions are needed		√	"easy" and "hard" disruption questions can be based off examples given in previous question
Questions/statements are concise			
Comprehension			
Questions/statements are devoid of academic language			
Questions/statements are easy to understand			

Aspects of an Interview Protocol	Yes	No	Feedback for Improvement
Interview Protocol Structure			
Beginning questions are factual in nature	✓		
Key questions are majority of the questions and are placed between beginning and ending questions		✓	there aren't really "ending questions"
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments		✓	should end with "is there anything else you'd like to share?" or something similar
A brief script throughout the interview protocol provides smooth transitions between topic areas	✓		
Interviewer closes with expressed gratitude and any intents to stay connected or follow up		✓	would be good to include; let them know when you will follow up
Overall, interview is organized to promote conversational flow	✓		
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)	✓		
Only one question is asked at a time	✓		
Most questions ask participants to describe experiences and feelings		✓	not much emphasis on feelings
Questions are mostly open ended	✓		
Questions are written in a non-judgmental manner	✓		
Length of Interview Protocol			
All questions are needed	✓		
Questions/statements are concise	✓		
Comprehension			
Questions/statements are devoid of academic language	✓		
Questions/statements are easy to understand	✓		

Aspects of an Interview Protocol	Yes	No	Feedback for Improvement
Interview Protocol Structure			
Beginning questions are factual in nature	✓		E could you introduce yourself? & your role as .....
Key questions are majority of the questions and are placed between beginning and ending questions	✓		
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments		✓	Add a closing statement, and opportunity to share their view.
A brief script throughout the interview protocol provides smooth transitions between topic areas ,	✓		Write down the figure explanation too!
Interviewer closes with expressed gratitude and any intents to stay connected or follow up		✓	
Overall, interview is organized to promote conversational flow	✓		
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)	✓		Need refinement. Clear questions...
Only one question is asked at a time	✓		
Most questions ask participants to describe experiences and feelings		✓	
Questions are mostly open ended		✓	
Questions are written in a non-judgmental manner	✓		
Length of Interview Protocol			
All questions are needed	✓		
Questions/statements are concise		✓	Combine few questions in one
Comprehension			
Questions/statements are devoid of academic language	✓		Except the figures in end,
Questions/statements are easy			

Aspects of an Interview Protocol	Yes	No	Feedback for Improvement
Interview Protocol Structure			
Beginning questions are factual in nature	✓		I think easing in is a good appr.
Key questions are majority of the questions and are placed between beginning and ending questions	✓		vocabulary check with Dr. Markam
Questions at the end of interview protocol are reflective and provide participant an opportunity to share closing comments	✓		
A brief script throughout the interview protocol provides smooth transitions between topic areas	✓		
Interviewer closes with expressed gratitude and any intents to stay connected or follow up	✓		
Overall, interview is organized to promote conversational flow		✓	"How large is your SCN" should come after definition is concluded with the question
Writing of Interview Questions & Statements			
Questions/statements are free from spelling error(s)	✓		As far as I can tell.
Only one question is asked at a time	✓		
Most questions ask participants to describe experiences and feelings	~	~	I think it might be more their perspective.
Questions are mostly open ended	✓		
Questions are written in a non-judgmental manner	✓		
Length of Interview Protocol			
All questions are needed	✓		
Questions/statements are concise		✓	not allway but a multiple choice and open ended are conflicting responses
Comprehension			
Questions/statements are devoid of academic language		✓	
Questions/statements are easy to understand	~	~	

APPENDIX C: Final Interview-Research Questions Matrix

Interviewee Name: ________________ Interviewee Company: ________________	Date: ________________ Start time / End time: ________________

Initial Introduction:
Good morning (afternoon), thank you for agreeing to meet today! My name is Bryce Schuebert, and for my engineering thesis, I am researching a production method called mass personalization (MPP), which allows individual consumers to participate in the design process in a cost-efficient and scalable manner. My research goal is to find out if there are commonalities, or vulnerabilities, in mass personalization supply chain networks (SCN) when facing disruptions such as COVID-19. To do this, I am conducting a series of interviews with various MPP companies to build proxy models of their SCNs, and then by examining the type and characteristics of each networks, I can identify potential patterns. These patterns can provide a deeper understanding of the strengths and weaknesses of an MPP supply chain.

Recording and Name Permission:
Our interview will last 30 to 45 minutes, but you are welcome to stop at any time. Before we begin, I would like to record this interview, so that I can gather all the necessary information for further analysis to remain present and focused on your answers. Do I have your permission to record A/V? I only intend to use the audio to generate meaningful insights from this interview. I will delete them permanently after transcribing.

If yes: Thank you! I will go ahead and begin recording now. Last question before we start: do I have your permission to use your name/companies name in my thesis and publication? This will just be used as background information about your company's unique production method. However, if you'd prefer to keep yourself and your company confidential, that is perfectly understandable and will not affect my research.

- ➔ *If yes*: Great, if you change your mind at any time, or would like to leave certain elements out, please just let me know.
- ➔ *If no*: I understand. I will keep your name and your company's name anonymous.

If no: That is fine; I will just take notes while you talk. Last question before we start: do I have your permission to use your name/companies name in my thesis and publication? This will just be used as background information about your company's unique production method. However, if you'd prefer to keep yourself and your company confidential, that is perfectly understandable and will not affect my research.

- ➔ *If yes*: Great, if you change your mind at any time, or would like to leave certain elements out, please just let me know.
- ➔ *If no*: I understand. I will keep your name and your company's name anonymous.

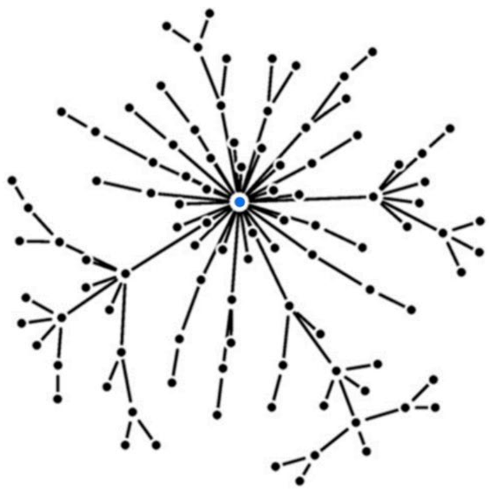
Before we begin, do you have any questions? [Discuss questions]
Please feel free to stop and ask any questions; I would be more than happy to answer your questions.

Begin Semi-structured Interview						
RQ1: What type of network topology most accurately represents a mass personalization supply chain network? **RQ2: How does the network topology impact supply chain functionality?**	Background Information	SCN Makeup	SCN Selection	Robustness --- *withstand a disruption's impacts*	Resilience --- *restore functionality after disruption*	Disruptions --- *node or network-level*
Interviewee Introduction *I'd like to start by asking you a few general questions.*						
IQ1. How long have you been with COMPANY NAME*?*	X					
IQ2. What is your current role within COMPANY NAME*?* ***Probe***: How familiar are you with your supply chain network?	X					
IQ3. What type of companies are your primary competitors?	XX		XX			
COMPANY's **SCN Structure** *Thank you for sharing information about your background. I'd like to transition to talking about how COMPANY supply chain network.*						
IQ4. How large is your SCN? *This could be a rough estimate* ***Probe***: *Is it a global SCN?*		XX				X
IQ5. How many COMPANY NAME manufacturing facilities operate?		XX				

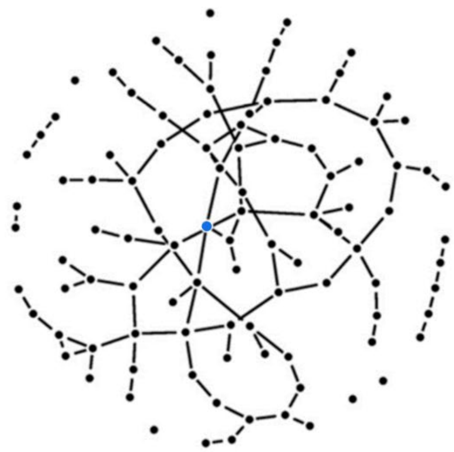
IQ6. When a product leaves your facility(s), what are all the ways it can get to the consumer? *Straight to consumer, through a distributor, from a retailer, hybrid, etc.* ***Probe if dist. or retailer exists****: How many distributors and/or retailers are in your network?*		X				
IQ7. Say a disruption like COVID-19 makes you have to switch to a new supplier. Are there specific preferences when choosing a new/replacement supplier, distributor, or retailer? ***Probe:*** *Preferences could include geographical location, company reputation or age, cost of business, etc.* ***Preferential attachment***			XX	X	X	
IQ8. Faced with a disruption, do you have redundancy in your supply chain? ***Probe:*** *Where is there redundancy and why?* ***Probe:*** *Is that normal practice?* ***Buffer***		XX	XX	XX		

IQ9. How many tiers deep is your supplier network? **Probe**: *Do you know a rough estimate of the total number of suppliers in your SCN?*		XX				
IQ10. Do you know if your suppliers communicate or collaborate with each other? **Probe**: *If so, is it across supplier tiers?* ***Clustering***		XX		XX		
IQ11. Do your competitors use the same suppliers?			X		X	
IQ12. How quickly could you recover if a supplier were to go OOB overnight? **Probe**: *Are there certain suppliers whose going OOB would affect you more than others?*					XX	
Disruptions *Thank you for sharing information about COMPANY's supply chain. I'd like to transition to talking about COMPANY's history of overcoming disruptions such as COVID-19*						
IQ13. Please tell me about an example of an "easy" disruption that you were quick to recover from. Why was it easy? *Use a supplier shortage or missed deadline here if needed* **Probe**: *Same question, but hard.*					XX	XX

Use COVID-19 here if needed ***Probe if short answer*: *How did you recover?***						
IQ14. In those examples, did you know the origin of the disruption or was it network-wide? ***Probe*:** If you know the origin, was it upstream/downstream? ***Visibility***				XX	XX	XX
IQ15. Do you think the makeup of your supply chain network impacts how quickly you can recover from a disruption? ***Probe*:** If so, could you provide any examples?		XX	X		XX	XX
IQ16. Below are two supply chain networks with each dot representing a company and each line representing a relationship. The blue dot signifies your company. Which network do you believe best represents your SCN? ***Probe:*** *Why?* *Show picture of scale-free and small-world networks*		X				X



A supply chain network with your company as a focal firm



A supply chain network with your company as one of many tightly clustered companies

(Airoldi et al., 2011)

IQ17. As an expert in the field, what are relevant questions that you think we should be asking other companies like yours as it relates to disruptions? What would you like to know about your counterparts in other corporations?						
IQ18. Do you have any comments, or questions for me?	X					

Closing Remarks

All questions answered?

If yes: That was my final question. Thank you very much for participating in this interview, and I am grateful for your responses. {Reiterate that name/company will remain confidential if necessary}. I will send out my final results to you in a few months. Please feel free to reach out with any questions at my email bryce@uga.edu.

If no: Thank you very much for participating in this interview, and I am grateful for your responses.

- ➔ *If a lot of specifics are missing:* Would you happen to have an internal contact who might be able to provide specific numbers for the {questions} within your organization?
- ➔ *If some specifics are missing:* Would it be alright if I sent a short questionnaire just to clarify some of the specifics from earlier?
- ➔ *If time runs out:* We ran out of time, so would it be alright if I sent a short questionnaire of the remaining questions?

. I will send out my final results to you in a few months. Please feel free to reach out with any questions at my email bryce@uga.edu.

APPENDIX D: Initial notes of the Interview Transcription

Tessa

- Global supplier network
  - Relatively small (Asia, central America, not in Europe anymore)
- 3 methods to get to consumer: 3PL, straight to consumer, 1 retail outlet
  - Global consumer market
- Their own distributor
- Supplier partners are chosen on specialty knowledge and active participation in item creation
- Not a lot of supplier redundancy
  - Trade-off between redundancy and lead-time for quality control
- Tier 1: "Middle men" [QTY: 5-7], Tier 2: "Factories" [15-20ish], Tier 3: "Mills" [7]
  - Direct relationships with all three tiers
  - Specialty fabrics means mill relationship is important
- Some shared suppliers with competitors
  - Difficult to not share some specialty suppliers
- One supplier providing 50 percent of line from a single supplier
  - Could be a significant vulnerability
  - Hints at "relatively high confidence" that they wouldn't go OOB.
  - Believes tier 2 could go OOB
  - 150-200 lead time (days) to switch to another Tier 1
- COVID really affected global shipping lead times
  - Still affected with material costs
- Was able to pivot and iterate new designs quickly due to responsive suppliers
  - COVID hit, and had iterated within two months (masks in may)
- They can hear about shortage of yarn but don't know where or why
  - "Suppliers don't really share that information"
  - Network wide shortages
- Before 2020, majority of suppliers were in China & Taiwan, now in China, Taiwan, Indonesia, Vietnam

    - Helped avoid competitor's COVID failures
- See's their SCN as a single upstream branch with everything else being downstream
    - This clarification might indicate small-world properties
- Interested in understanding how their competitors source their supplies

Ken

- Familiar with SCN since it's a small company
- Competitors are suppliers to automotive companies and prototype injection molding
- Suppliers are primarily raw material suppliers for injection molds and resins
    - Sounds like a Tier 2 company?
    - List of "qualified suppliers"
- Raw material is coming from distribution centers, unsure where the centers get the raw material.
- Consumers are from around the world (Spain, Russia as examples)
- Two Protojet manufacturing facilities
    - 1x tooling center and 1x production (runs parts)
        - Production plant runs custom tooling from center and also from other companies who've offloaded smaller production runs to Protojet to handle
    - 45 min away from each other
        - Geographically strategic?
- COVID has caused
    - Material restrictions
    - Companies to "jack up" costs
        - Believes half due to supply/demand and half due to taking advantage of situation
        - Passed costs to consumers
    - Can't mark up material too much since it is easy to price check
- Final products are shipped globally and can get to destination via:
    - Directly to consumer
    - Through distributor to then be sold online or distributed to companies
    - If automotive, parts goes to warehouse then to assembly plants
- Suppliers are chosen based on their ability to perform required task and location
    - Sometimes suppliers are used in different countries if requested by consumer
        - Specialized material example used
    - Generally, suppliers are local so they can follow up
    - 35 – 50 suppliers
- Multiple distributors for raw materials
    - Has back up plan but not a lot of redundancy for manufacturing
        - Lack of redundancy due to specialization

- Suggests they're a tier 1, 2 & 3, depending on who is asking for what
    - Refers to the company as a black box company
        - Not design responsible
    - Settles on being a Tier 2 (probably) for automotive, Tier 1 for the typical consumer
- Smaller distributor network (than suppliers)
- Suppliers communicate to remain competitive
    - See the supply and prices of other companies to determine their own price
    - Isn't for sure which companies talk to who but said the big suppliers definitely talk
    - Said COVID has caused a little collusion between companies to keep prices high (speculation?)
- Competitors share suppliers
    - Use internet to find suppliers
        - 15 years ago it would be more difficult to find suppliers
- Suppliers of common material going OOB would not affect their product
    - Specialized materials would
    - Going out of stock is less worse than OOB
- Any material shortage that causes disruption with their automotive partners is a massive disruption
    - Said other shortages aren't as bad
- COVID wasn't bad in-shop since their company is pretty small but a lot of their consumers were shut-down (automotive) making delivery difficult
    - Materials were not available due to worker shortage/weird hours
        - **Didn't** mention any material shortage
- Initial statewide shut really affected the company, the following six months were also bad since other states had different rules, affecting suppliers/consumers
- He says network structure has a massive impact
    - Was brought on to grow the network
        - Offers faster service and lower prices since smaller company
- COVID made them find other businesses to work with and had to pivot their business model to survive
    - pivot to making face masks
- Said PPE loan really helped get through COVID
    - Must've been really tight?
- Said business is 60% automotive, 30 medical and commercial and 10% mix
    - Identified with the small-world network
- He wanted to know more about COVID's affects on the workforce and long-term effects on worker motivation

Greg

- Been with the Xometry since near its' inception and is very familiar with their SC

- Largest global manufacturing marketplace
  - Compared model to Uber
  - Consumer uploads their 3D model and AI/machine learning interprets the model to get instant pricing and lead times
  - Over a dozen manufacturing techniques
  - Order is automatically matched with a capable manufacturer
- Xometry is still responsive for the final product
  - Uses global network of suppliers for capacity
    - 5000 manufacturers (or suppliers?) making parts on Xometry's behalf
- Compared to Protolabs but they're not a marketplace network; they actually do their own manufacturing
  - Recently did acquire a much smaller scale marketplace
  - Other companies have been created to try and compete with their business model
- Recently acquired ThomasNet which is the largest global directory of manufacturers
  - 500,000 manufacturers
- "Basically, the infrastructure for manufacturing"
  - Indicates that they are helping both consumers and manufacturers, ensuring that the manufacturers are getting really good financial services (paid early, quickly, and regularly)
- Xometry themselves have a few manufacturing facilities in Maryland and a facility for QA
  - Does a lot of QA, so parts go to them as second QA before going to consumers
- Products on-demand custom and are either shipped B2C or B2B
  - Most are B2B
    - Often the consumer gets product for inventory and does distribution on their side
    - Used GE and NASA as example
- COVID had no disruptions for consumer domestically
  - Potential suppliers/manufacturers are geographically dispersed
  - If one manu passes on a product opportunity, it gets routed to the next available manu
  - If they get a "no take", Xometry reviews technical documentation to see if there's something about pricing or lead times. Then sent back out to network with updates, sometimes reaching out to suppliers manually
- Used Hurricane Harvey as example where local manus couldn't produce parts and other shops nearby were able to fill in
- Xometry has its own crisis center to track weather patterns and major events to be projective

    - Company is about 1000 people with a substantial ops team to keep projects running
- New suppliers can create their listing with capabilities in the marketplace
    - Qualified suppliers are further vetted
        - Sometimes required to produce a test part to qualify
        - They pay them to do this since it is worth not sending poor parts to the consumer
    - Each partner has a success score based "quality of product, their timeliness, interactions with the website, communication. But quality and timeless are by far the largest part of that metric there."
    - When first starting, they get lower value jobs and work their way up to high revenue opportunities
    - If partner not doing well, Xometry support works with them
        - Sometimes, suppliers are fired
- Xometry does tier 1 work for BMW for lower volume after-market parts
    - Isnt really defined by the tier system
- Xometry actually has Xometry Suppliers to supply their own manufacturers
    - Allows them to deliver earlier and makes sourcing of common materials easy
    - Xometry supplies has a headquarters that mainly hardware like cutting ools
        - Uses dropshipping agreements with other raw material suppliers
        - Serves as a centralized location
    - Has strategic sourcing teams to locate critical supplies
- Suppliers/manufacturers talk with each other through community forums
    - With newer technologies and apprenticeships dying out, forums help learn software quickly
    - Forums also provide companies some visibility with current events
        - Xometry has a whole team that reach out to manu with tips and resources as well
- Says competitors have the opportunity to use their suppliers
    - Compared it to Uber and Lyft drivers
- Earlier on, when Xometry had a full machine shop in-house, they ran into backlog issues
    - Said that's why the current model works so well; large orders can be dispersed to different shops to help fulfill orders quickly
- Typical disruptions occur when manus getting used to a new process make an error or weather events
    - COVID caused disruptions with shops going up and down depending on state-wide restrictions across the country
    - Chinese New Year was extended a month, and Chinese consumers were still able to get their product from the US for a small price change (Global redundancy)

- Stated that Xometry's SCN is extremely resilient
  - Most disruptions occur from consumers changing project scope
  - Or when consumer expectations are not met
  - Or when consumers ask for something without the "technical package" (dimensions, 3D model)
    - This happened a lot in the pandemic
    - Most people came expecting a catalog to chose from but Xometry is on-demand
    - During COVID, NIH's repository of solutions allowed Xometry to present options to consumers
- Biggest challenge is not supplier related but insufficient technical data

- Says network is most like small-world, connecting everything together
- Wanted to know how other companies adapted to COVID's disruptions
  - Add assembly services during pandemic for consumers, becoming the kitter / vertically integrating (example of adaptation on their part)
  - Were able to give 200 manufacturers critical certificates to keep running their shops during COVID

APPENDIX E: Gephi Python Code

```
# import
from gephistreamer import graph
from gephistreamer import streamer
import random

# https://github.com/totetmatt/GephiStreamer
# Create a Streamer connection to Gephi (source URL:
http://localhost:8080/worskpace1) Change workspace name if necessary
stream = streamer.Streamer(streamer.GephiWS(hostname="localhost",
port=8080, workspace="workspace14"))

# Once stream is created, the nodes might be invisible. Click Show Node
Labels, then change layout to Label Adjust and run. Now select another
layout if necessary
##################################
# Ministry of Supply
# Suppliers
t3 = 7
t2 = random.randint(15, 20)
t1 = random.randint(5, 7)

# Focal firms
ff = 1
```

```
# Retailers
r = 1

# Create a node with a label
# Suppliers
# Create unique IDs for each node using list comprehension
t3_list = [graph.Node(f"t3_firm{n+1}", label="T3") for n in range(t3)]
# Add all nodes from list to gephi
stream.add_node(*t3_list)
t2_list = [graph.Node(f"t2_firm{n+1}", label="T2") for n in range(t2)]
stream.add_node(*t2_list)
t1_list = [graph.Node(f"t1_firm{n+1}", label="T1") for n in range(t1)]
stream.add_node(*t1_list)

# Focal firm
ff_list = [graph.Node(f"FF{n+1}", label="FF") for n in range(ff)]
stream.add_node(*ff_list)

# Retailer firm
r_list = [graph.Node(f"R{n+1}", label="R") for n in range(r)]
stream.add_node(*r_list)

# Create edge
# Link function with regular probability of connection between firms
downstream
def link(source, target, p):
    for u in source:
        for v in target:
            # For each node in list u, connect it to each node in list v
if the random [0,1] is < than the given probability
            if random.random() < p:
                # Prevent self-loops
                if u != v:
                    # Create edge between the two nodes
                    edge = graph.Edge(u, v, directed=False)
                    # Add edge
                    stream.add_edge(edge)

# Link T3, T2, T1 together with a likely probability
link(t3_list, t2_list, .2)
link(t2_list, t1_list, .2)

# Link T1 to FF and FF to R
link(t1_list, ff_list, 1)
```

```
link(ff_list, r_list, 1)

# Link Tiers and FF together with lower probability
link(t3_list, t1_list, .14)
link(t3_list, ff_list, .18)
link(t2_list, ff_list, .18)

# Link same tiers with low probability
# Note: The probability differs depending on the list size (bigger list of
nodes needs a smaller probability)
link(t3_list, t3_list, .1)
link(t2_list, t2_list, .06)
link(t1_list, t1_list, .1)

##################################
# ProtoJet
# Suppliers
s = random.randint(35, 50)

# Focal firms
ff = 2

# Distributors
d = random.randint(10, 15)

# Create a node with a label
# Suppliers
s_list = [graph.Node(f"s_firm{n+1}", label="S") for n in range(s)]
stream.add_node(*s_list)

# Focal firm
ff_list = [graph.Node(f"FF{n+1}", label="FF") for n in range(ff)]
stream.add_node(*ff_list)

# Distributor firm
d_list = [graph.Node(f"D{n+1}", label="D") for n in range(d)]
stream.add_node(*d_list)

# Create edge
# Link function with regular probability of connection between firms
downstream
def link(source, target, p):
    for u in source:
        for v in target:
            if random.random() < p:
```

```
                    # Prevent self-loops
                    if u != v:
                        edge = graph.Edge(u, v, directed=False)
                        stream.add_edge(edge)

# This function is to disperse links to multiple focal firm facilities
def link_focal(source, target, p):
    for u in source:
        # Select one of the focal firms to connect
        i = random.randint(0, len(target)-1)
        v = target[i]
        # Prevent self-loops
        if u != v:
            edge = graph.Edge(u, v, directed=False)
            stream.add_edge(edge)
        # Possibly connect to another FF facility
        if random.random() < p:
            target_cpy = target[:]
            target_cpy.pop(i)
            # Prevent empty list
            if len(target_cpy) != 1:
                i = random.randint(0, len(target_cpy)-1)
                v = target_cpy[i]
                edge = graph.Edge(u, v, directed=False)
                stream.add_edge(edge)
            else:
                v = target_cpy[0]
                edge = graph.Edge(u, v, directed=False)
                stream.add_edge(edge)

# Link S together with reg. probability
link(s_list, s_list, .06)

# Link suppliers to FF and FF to D directly
link_focal(s_list, ff_list, .1)
link_focal(d_list, ff_list, .1)

# Link distributors
link(d_list, d_list, .04)

##################################
# Xometry
# Suppliers
s = 5000
```

```python
# Focal firms
ff = 6

# Create a node with a label
# Suppliers
s_list = [graph.Node(f"s_firm{n+1}", label="S") for n in range(s)]
stream.add_node(*s_list)

# Focal firm
ff_list = [graph.Node(f"FF{n+1}", label="FF") for n in range(ff)]
stream.add_node(*ff_list)

# Create edge
# Link function with regular probability of connection between firms
downstream
def link(source, target, p):
    for u in source:
        for v in target:
            if random.random() < p:
                    # Prevent self-loops
                    if u != v:
                        edge = graph.Edge(u, v, directed=False)
                        stream.add_edge(edge)

def link_focal(source, target):
    for u in source:
        # Select one of the focal firms to connect
        i = random.randint(0, len(target)-1)
        v = target[i]
        # Prevent self-loops
        if u != v:
            edge = graph.Edge(u, v, directed=False)
            stream.add_edge(edge)

# Link S together with reg. probability
link(s_list, s_list, .0001)

# Link suppliers to FF and
link_focal(s_list, ff_list)
```