Comparison of Short vs Conventional networks to alleviate food insecurity through supply chain resilience.

Author: Pedram Bagheri

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Abstract

This study presents a pioneering quantitative comparison of the resilience and performance of short and long supply chains in the face of disruptions. The case study on raspberry production is conducted to perform this analysis. Through a comprehensive simulation framework, we analyze and compare a localized supply chain in the Northwest Territories of Canada against a long-distance supply chain importing raspberries from Mexico. This research makes a unique contribution to the field by quantitatively evaluating the performance and resilience of both short and long supply chains. Through a disruption history encompassing 54 varied scenarios, this study enables a clear, data-driven judgment of the two supply chain networks. This approach moves beyond the traditional reliance on qualitative and theoretical advantages, offering an empirical basis to compare their efficiency and robustness under disruptive conditions. The findings reveal significant insights into the costs, efficiency, and robustness of both supply chain models. The model developed here applies seven different network compositions for short and long supply networks to the 54 disruption scenarios, picking the optimal network overall in each scenario, leading to an average 5.2 percent increase in resilience, all while reducing costs by $ 4500. Importantly, the methodology and framework developed in this study are not confined to raspberry production; they hold potential for broader application across various supply networks. This aspect is particularly valuable for entrepreneurs and businesses in evaluating the feasibility and resilience of new ventures. Moreover, our findings offer actionable insights for governmental bodies, like the Government of Canada, in strategizing to incentivize local production. This approach could be

a crucial step towards ensuring national food security and stabilizing food prices across the country, thereby having significant implications for policy-making and economic planning.

Chapter 1 Introduction

Historically, human civilization has depended on agriculture for sustenance and growth. With the burgeoning global population, agricultural practices have evolved towards industrialization to meet increasing demands. However, this globalized agri-food supply network introduces heightened risks, as witnessed during the COVID-19 pandemic. The pandemic highlighted the vulnerabilities of current supply networks, leading to a renewed interest in local products, particularly in urban areas of Canada.

Short supply chain is a term that refers to networks where production zones and consumption zones are directly connected with the least possible intermediaries. The shortened path of a short supply chain leads to lower carbon footprints, lower transportation costs, a sense of belonging, an overall increase in sustainability, and provides consumers with fresher and more nutritious food options. These benefits have spurred policymakers and companies to explore the potential of short food supply chains in meeting food security needs amidst continual disruptions.

The risks associated with the conventional food networks alternatively translate into heightened costs of family's food baskets, leading to an increase in the number of people who struggle with accessing the healthy and nourishing diet they need to thrive. The severity of this problem is showcased in the following statistics (Maple Leaf Food, 2023):

-Approximately 6.9 million people in Canada face challenges in obtaining necessary food.

-Around 17.8% of households in Canada experience food insecurity.

-Food insecurity impacts one out of every four children in Canada.

-Half of the individuals aged 15 and above in food-insecure households in Canada live with a disability.

-The prevalence of food insecurity in Indigenous and Black households in Canada is more than double the rate found in other Canadian households.

The above statistics clearly indicate the dire need for collaboration and attention from different stakeholders to battle food insecurity in Canada. Surprisingly, this situation is not caused by a scarcity of food, but by poor distribution systems, especially in geographically, racially, or economically isolated demographics. In fact, the statistics show that a whopping forty percent of grown food is not consumed. Therefore, we decided to enhance the distribution aspect of the food industry to reduce waste and the price of food and increase its availability in areas where it is needed the most, providing people with better nutrition and an equal chance of thriving as a result.

The main purpose of this research is to assess and compare the resilience of different types of agri-food supply chains in Canada; namely, short-food supply chains and industrialized agri-food supply chain networks for Raspberries. By solving a real case of raspberry production, we compare the performance of the two supply chain networks. This comparison is crucial in an attempt to reduce the costs of providing food to consumers and to alleviate food insecurity in Canada, a challenge that is particularly pronounced in the context of perishable goods like raspberries. These goods face unique challenges, such as high retail prices and a notably short perishability period, significantly impacting the supply chain dynamics. Switching from conventional to short supply chains faces multiple challenges, such as the complexity of logistics, lack of government support, lack of public awareness, and limited access to capital. Through the holistic comparison in this research, we facilitate transportation services, increase government inclination towards supporting these networks, increase knowledge of the nature of these networks, and justify the capital investment required to engineer these types of food networks. Additionally, an underlying goal of this research is to reduce the ambiguity that surrounds the definition of short supply chains. This is achieved by increasing the size of the network to the point where its tendencies and characteristics shift. As a result, we analyze the pivotal point at which stark differences in the performance of the networks appear.

The first step we took in defining our research agenda was understanding food networks, and later the cost and performance parameters of these networks. The major costs pertinent to the food network include but are not limited to the cost of raw materials, seeds and fertilizers, transportation costs, labour costs, tools and machinery costs, processing and packaging costs, and storage costs.

We realized that to reduce the costs, we needed to boost the performance parameters of the supply network. Therefore, this research seeks a concept that examines the intricacies of costs and supply chain performance. This concept is called supply chain resilience.

1.1 Supply Chain Resilience

Resilience is defined as the ability of a supply network to handle disruptions and recover from them as rapidly and efficiently as possible. These disruptions range from road closures to natural phenomena such as wildfires, earthquakes, floods, and pandemics, which are unpredictable and inevitable. The significance of resilience becomes even more crucial when considering the delicate balance required in the raspberry supply chain, where timely delivery and freshness are paramount. The resilient network will incur lower costs in producing, processing, and delivering food to the final consumer.

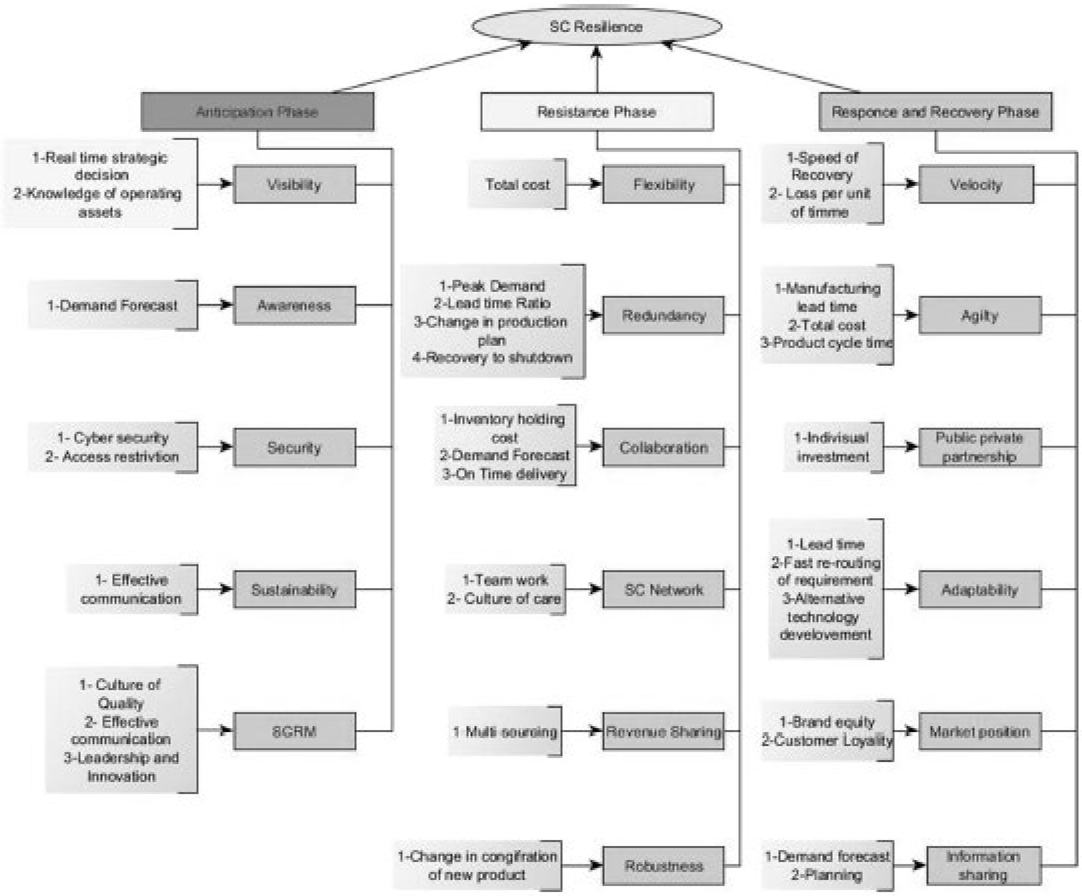


Figure: 1-1 Supply chain resilience framework (Clavijo-Buritica et al, 2023)

A schematic diagram on the supply chain network is shown in Figure 1.1. To assess resilience, we combine a hybrid method of simulation and optimisation; first we simulate a short supply network of raspberry distribution in the northwestern territories of Canada. Later we simulated a conventional supply network where raspberries are produced in Mexico and then exported to the same consumer zone. In the optimisation phase, we use mathematical modelling to optimise the resource allocation to minimize costs and, eventually, waste.

1.2 Resilience metrics

This research focuses on two critical resilience metrics: connectivity and availability. These factors are particularly relevant in remote areas of Canada where food insecurity is most acute.

Availability assesses whether consumption zones have access to supplies to continue their operations, while connectivity refers to the largest functional subnetwork post-disruption, ensuring all nodes are connected with at least one supply zone. Using such metrics allows us to step away from the qualitative definitions of different supply networks' performance and quantitatively measure and compare them.

Like any other phenomenon in nature, precise understanding of its nature and intricacies relies on mathematical modeling of said phenomenon. Therefore, the resilience of these supply networks is quantified using the following formula.

$RLS= 1/TC * Con\ (\%) * Avl\ (\%)$ ------------------------- Equation 1-1

where RLS represents Resilience, TC represents the total cost of production, holding, and transportation, Con represents the connectivity of the network, and Avl represents the availability of the network. This formula allows for a direct, quantitative comparison of the resilience between short and long supply chains, moving beyond qualitative assessments and focusing on empirical data, deepening our understanding of resilience. The same formula was applied to both networks to calculate the respective resilience and compare them to better understand their adaptability, flexibility, agility, and risk management. On top of that, the pinch points in both supply chains were identified so that future vulnerabilities could be dealt with proactively. Adaptability is the ability of the network to sustain its performance and even flourish in the face of disruptions. Agility is the pace at which the network does this. Flexibility refers to how proactive the network was before disruptions occurred, so when they did it could transition accordingly. Risk management is the willingness of a network to allocate resources to prevent disruptions from crippling the network.

1.3 How the resilience is measured

As mentioned earlier, to better understand a phenomenon, measuring it is the first process that comes to mind. We measure resilience using total cost, connectivity, and availability. These are then calculated using a mathematical model comprising production, storage, and transportation costs. Additionally, the number of customers with access to distribution zones and the size of the network that has a functional flow of products are measured to derive connectivity and availability respectively. Total cost calculates all the costs incurred to the network by every single movement, resource used, and product storage. Connectivity and availability are other factors that define the state of said movements. In other words, how easy it is for consumer zones to access the production zones and how fluid the network is. Through this measurement, we can develop and adjust the supply chain network in an attempt to maximize its performance both prior to and after disruptions.

1.4 **Short and conventional supply chain networks**

The two types of networks we are specifically interested in are short and long supply chains. First, we define the differentiating factor between the two, which is the number of parties involved. If the number of all the stakeholders of the network does not exceed 3 (Producers, Retailers, and Consumers), we call that network short. If there are additional intermediaries involved that supply chain network is known as long (Kneafsey M et al, 2013). In order to measure these networks against each other we first developed them for a specific consumer zone (Northwestern Territories of Canada in this case) and later added more complexity to both networks to remove the role that plays in the performance of the supply chain networks. Ultimately, using the mathematical model developed for measuring the resilience of these networks the ideal network and the corresponding level of complexity is identified.

1.5 **The supply chain distribution network**

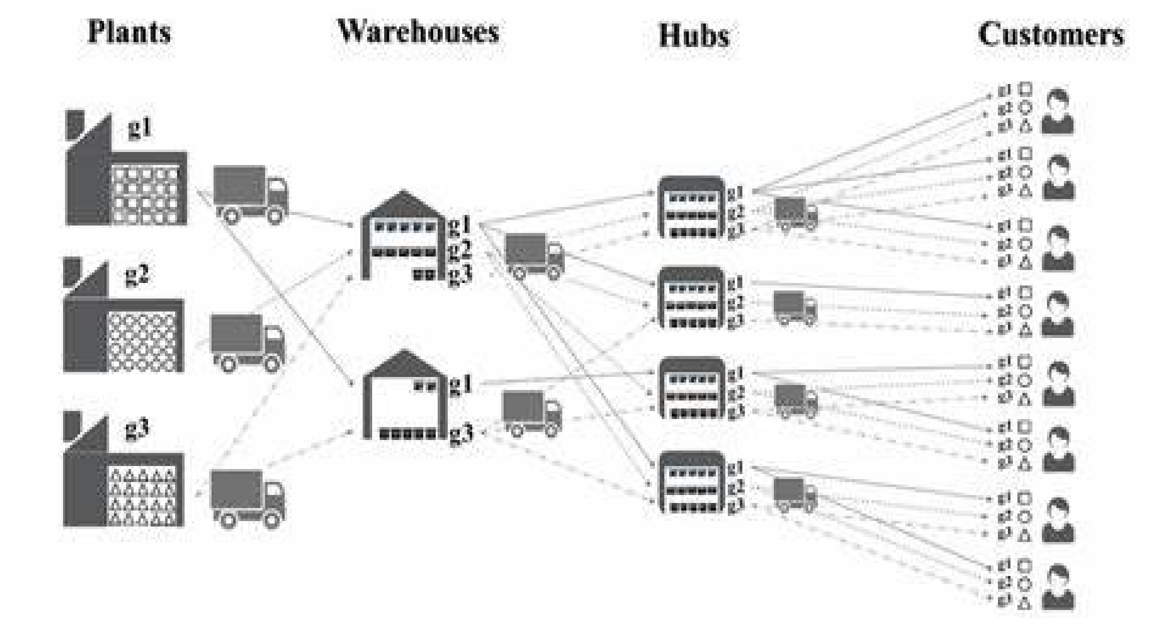


Figure 1-2 Supply chain connectivity network

The overarching goal of this research is to determine if shortening the value chain — reducing intermediaries and focusing on localization — can mitigate risks associated with natural phenomena and lower the final price of food products. This could, in turn, enhance the resilience of the food network. Such insights are pivotal in revising agri-food networks to better manage disruptions and increase efficiency.

The research path we embarked on is as follows; first, we identified a problem which affects large sums of the Canadian population and is becoming increasingly relevant as food prices soar, resulting in food insecurity. One of the major solutions to this problem is reducing the final price through increasing the efficiency of the supply network. One of the prominent solutions to the efficiency problem is increasing the resilience of the network. The footprint of resilience is especially magnified in the food industry, where shelf life plays a pivotal role. The specific product we decided on studying is raspberries, which are both produced locally and imported from neighboring countries such as the United States and Mexico. This in turn allows us to compare the performance of both conventional and short supply networks so we can identify and design the most resilient network. Therefore, the quantitative model is developed around three major variables, total cost, availability, and connectivity to make a holistic comparison between different food networks. These models are later introduced to disruption scenarios which are simulated to make the disruption history of both networks, so the performance of these two networks can be assessed under similar conditions. Finally, all the performance metrics are calculated to compare how local networks perform against the global networks in terms of resilience and identify the gaps and chokepoints that can be modified to enhance said performance.

1.5 Overview of the thesis

This thesis goes on to extensively discuss the previous work done in papers on the subject of supply chain resilience and its measurement in chapter 2. Then it defines short and conventional supply chains and the possible benefits and shortcomings of each of them separately.

Later in chapter 3, we dive deep into the mathematical model to measure the performance of the supply network and build a mathematical model to optimize the network flow. The mathematical model minimizes total costs subject to the limited available resources. The two networks under study are simulated and the disruption history for both is developed through the remainder of this chapter.

Chapter 4 is where the networks developed earlier are applied against the disruption history simulated to calculate their resilience and cost performance. These are later analyzed in chapter 5 to draw conclusions and compare the performance of each supply chain type separately. In the end, the managerial insights are noted accordingly.

Chapter 2 Literature Review

The first step in identifying and addressing any gaps in the body of literature is to dive deep into the existing literature on food supply networks' resilience.

2-1- Resilience

We choose resilience as our prominent performance measure in order to better understand and compare the validity of the food networks we simulate.

2-1-1- What is resilience?

Resilience originates from papers that study risk management. However, later the need for a holistic proactive approach towards disruptions called for an enriched concept which involves not only risk management, but also adaptability, flexibility, and agility. Risk management refers to preparing the network in a manner that is able to respond to unforeseen events, adaptability is the network's potential to operate under the new reality of the disrupted market, flexibility is the ability to alternate between the pre-developed frameworks according to the disruption, and agility is the speed to which a network responds to and recovers from a disruption.

In short, the idea of resilience was developed as how well a supply chain can adapt and respond to unforeseen events that are beyond its control. Therefore, the vulnerabilities of a network must be identified in advance. As mentioned in (Herrera-Araujo et al., 2021), when vulnerabilities at critical points in the supply chain are reduced, the overall resilience of the supply chain increases. Hence, resilience and vulnerability are interconnected concepts that should be considered together. When resilience increases, vulnerability decreases, and when vulnerability reduces resilience increases. Based on Lorimer et al (2018)'s analysis of resilience strategies with a conclusion that blockchain-coordinated supply chain disruptions create a ripple effect, therefore, identifying the weak points and making that node of the network resilient decreases the severity of the disruptive wave that hit all the layers of the supply network, from farmers to producers, distributors, and consumers.

2-1-2- How the resilience is measured?

Supply chain networks are complex systems that involve multiple parties, including suppliers, manufacturers, distributors, and customers (Govindan & Fattahi, 2021). The resilience of these networks is crucial for their sustainability and ability to withstand unexpected disruptions. Backed by the comprehensive studies that delve into the conceptual definition of resilience and its factors, a handful of papers have analysed resilience quantitatively in order to provide measuring tools for researchers and practitioners. Among these methods, simulation-optimization methods have been widely used to design and assess resilient supply chain networks under uncertain scenarios (Govindan & Fattahi, 2021). Their research presents a comprehensive classification of uncertainty scenarios that can affect supply chain networks, including demand uncertainty, supply uncertainty, transportation uncertainty, and environmental uncertainty. Therefore, to capture the full intricacies between uncertain vulnerability scenarios and resilience, a hybrid method of simulation and optimization should be adopted.

The first group of the papers focus on simulation-based methods. These methods involve constructing a simulation model of the supply chain network and using it to simulate different scenarios to evaluate the resilience of the network. The review presents various simulation-based methods, including discrete event simulation, system dynamics, and agent-based modeling (Govindan & Fattahi, 2021). Simulation models aim to assess the impact of disruptions and evaluate the effectiveness of mitigation strategies. For example, Yu et al. (2020) developed a simulation model to analyze the impact of COVID-19 on the supply chain of a medical equipment manufacturer. The model incorporates various factors such as transportation disruptions, production capacity, and demand uncertainty, and provides insights into the impact of different mitigation strategies (Syntetos et al., 2021).

The second group of papers focus on optimization-based methods. These methods involve formulating the design and operation of the supply chain network as an optimization problem and using mathematical programming techniques to find the optimal solution. The review presents various optimization-based methods, including integer programming, stochastic programming, and robust optimization (Govindan & Fattahi, 2021). Optimization models aim to minimize the impact of disruptions by optimizing the allocation of resources, inventory, and production planning. For example, Zhang et al. (2020) proposed a multi-objective optimization model to minimize the impact of disruptions on the supply chain while maximizing the profit of the firm. The model considers the demand uncertainty, production capacity, and transportation costs, and provides insights into the optimal production and inventory decisions (Syntetos et al., 2021).

The third category of papers focuses on hybrid simulation-optimization methods. These methods combine simulation and optimization techniques to leverage the strengths of both approaches. The review presents various hybrid simulation-optimization methods, including discrete event simulation-based optimization, system dynamics-based optimization, and agent-based modeling-based optimization (Govindan & Fattahi, 2021).

Lastly, there are papers that focus on the SCR index as a measure of a supply chain's ability to withstand disruptions and recover quickly. It is typically calculated based on a set of indicators such as flexibility, redundancy, agility, and visibility. However, the challenge lies in determining the weights of these indicators and how they interact with each other. The graph theory-based approach provides a solution by representing the supply chain as a network of nodes and edges, where nodes represent the entities in the supply chain and edges represent the relationships between them (Wang et al., 2016).

In this research, we adopt a mixture of the aforementioned papers to build on the quantitative basis laid by previous authors and create a model that assesses the severity of disruptions and the resilience of two studied networks under the simulated disruptions; short supply chains and conventional supply chains in the agri-food industry.

2-1-3- Why does the resilience matter?

The outbreak of COVID-19 has exposed the vulnerabilities of supply chains and highlighted the importance of supply chain resilience (Mishra & Gunasekaran, 2021).

A study by Patel et al. (2021) examined the supply chain resilience of Indian manufacturing firms during the COVID-19 pandemic. The study found that firms with diversified supply chains and those that had adopted digital technologies were more resilient during the pandemic than firms that relied on a single supplier or had not adopted digital technologies (Govindan & Fattahi, 2021). As a result, preparing resilient supply networks and testing them in advance help mitigate risks associated with unpredictable disruptions. These tests can be carried out using a framework that finds optimal network structure and allocation of resources while exposing them to disruptions well before they occur.

The first type of supply network we study is called Short Supply Chain. These are supply networks that soon became popular as potential alternatives to contemporary networks as they align with the more minimalist approach that later became popular in the world of business. Below we will describe the details, potentials, and limitations of these types of networks.

2-2- Short Value Chains

Short value chains eliminate most intermediaries by linking local producers directly with consumers, ensuring fresher products and reduced environmental footprints. They also foster regional economic development and enhance transparency, contributing to greater supply chain resilience in local communities.

2-2-1- What are short supply chains

Short food supply chains, or SFSCs, are food systems that involve direct connections between producers and consumers, bypassing intermediaries. (Mundler & Laughrea, 2016; Bui, 2014; Demartini et al., 2015). This can be achieved through local markets, farm stands, or other direct marketing channels. SFSCs are characterized by shorter distances between production and consumption (Galli & Brunori, 2013), which bring about a focus on sustainability, social equity, and local development (Goodman, 2004). They are recognized as a promising alternative to conventional food systems and often foster a sense of place and community (Campa & Goldberg, 2005). In other papers the same concept has been studied under the term alternative food networks, or AFNs, which are diverse, localized food systems that challenge the dominant industrialized food system. They are characterized by shorter food chains, local production, and direct relationships between producers and consumers (Mount, 2015).

The authors of the paper (Goodman, 2004) highlight the potential of AFNs for promoting sustainability. They also emphasize the need to understand the contextual factors that shape SFSCs in different regions, as they can vary widely from farmers' markets and community-supported agriculture to farm shops and box schemes (Goodman, 2004). These networks offer solutions to challenges faced by agriculture in urban areas, such as increasing land prices and limited space, by shortening food supply chains and maintaining agricultural activities near urban areas (Aubry & Kebir, 2013).

2-2-2- Their possible benefits

The past few years have seen rising attention towards alternative food networks including Sustainable Food Supply Chains (SFSCs) and Alternative Food Networks (AFNs) because they help reach sustainability goals and create social bonds while generating economic advantages for farmers and nearby communities. The research synthesis identifies multiple essential discoveries regarding this topic. Local food systems enhance sustainability by supporting local economies and community connections while delivering fresher and healthier food choices for consumers (Ohberg, 2013). SFSCs build social cohesion and trust between local stakeholders by enabling direct interactions and developing connections between producers and consumers (Mundler & Laughrea, 2016) and they advance trustworthiness and transparency while delivering fair prices to create social and economic justice (Galli & Brunori, 2013) (Vittersø, 2016). Increased cooperation together with knowledge sharing and collective action boosts local food systems and community resilience. SFSCs build community connections by re-establishing links between producers and consumers and support local food traditions and educational initiatives (Galli & Brunori, 2013). The authors of Aubry & Kebir (2013) discuss how shortening food supply chains supports food sovereignty through the empowerment of local farmers and the promotion of local food cultures while decreasing dependence on remote food sources.

SFSCs drive economic development through their support of local producers while generating new opportunities for small farmers and retail businesses. Through SFSCs farmers obtain equitable pricing for their products while consumers benefit from access to fresh and superior quality food grown nearby. Through local entrepreneurship and job creation local economies gain strength while they also decrease their reliance on external food sources (Mundler & Laughrea, 2016; Aubry & Kebir, 2013). According to Bui (2014) SFSCs promote economic resilience by minimizing reliance on global supply networks while also lessening risks from price fluctuations and concentrated markets.

SFSCs provide environmental advantages by decreasing food miles and associated carbon emissions through shorter transportation distances and less energy use while minimizing food waste and packaging which supports a circular economy (Vittersø, 2016; Goodman, 2004). SFSCs focus on sustainable farming practices including organic and agroecological methods that support biodiversity as well as soil health and water conservation (Demartini et al., 2015). The shift towards sustainable land management becomes particularly important as environmental degradation and climate change issues grow alongside the move towards reduced agrochemical use. The preservation of natural resources stands as an additional advantage linked to these networks according to Galli & Brunori (2013).

The developing nation of Vietnam (Bui, 2014) discovered identical advantages through short food supply chains such as increased farmer earnings and reduced transaction costs alongside better product quality and heightened environmental protection. Research indicates that short food supply chains deliver sustainable advantages for Vietnamese small farmers through better income opportunities, enhanced market access and diminished reliance on intermediaries.

Ultimately, short food supply chains improve food security and provide access to nutritious fresh food appropriate to local cultures in underserved regions (Demartini et al., 2015). According to Galli & Brunori (2013) and Maye & Kirwan (2013) SFSCs foster social cohesion and empowerment between producers and consumers while building more inclusive and resilient food systems. The qualitative benefits combined with the opposition of alternative food networks toward industrial food production and consumption systems inspired our team to develop a quantitative analysis method. A quantitative assessment method evaluates the resilience of SSCs while comparing them to traditional food networks.

2-2-3- The Local Food Movement: Barriers and Challenges

Recent years have seen growing support for the local food movement because both consumers and farmers aim to create sustainable systems which are resilient and community-oriented. The local food movement holds significant potential advantages but encounters various obstacles which constrain its expansion and influence. This section presents findings from several research studies and literature reviews to determine the primary obstacles and difficulties confronting the local food movement.

The studies pinpoint distribution and logistics as one of the key obstacles according to Mundler (2012). Local food producers face challenges in bringing their products to market because they have limited distribution networks together with inadequate transportation infrastructure and elevated transportation costs (Aubry & Kebir, 2013). Farmers who supply local food systems must often participate in direct-to-consumer sales through avenues like farmers' markets and CSA programs because these routes present substantial logistical challenges and demand a lot of time and effort. Diminished access to distribution channels such as grocery stores and restaurants along with institutional buyers limits consumer demand for local food products and restricts their market availability (Ohberg, 2013).

Outside distribution and logistics problems, another substantial obstacle for the local food movement includes missing supportive policies and regulations (Mundler, 2012; Galli & Brunori, 2013; Vittersø, 2016). The effectiveness and success of local food systems depend heavily on government policies and regulations. The local food movement encounters multiple barriers including inconsistent definitions and certification systems together with burdensome regulatory requirements and insufficient financial support for local producers. The predominance of large-scale industrial agriculture in mainstream food systems creates an unfair competitive environment for local food producers who must navigate regulatory and financial obstacles that big industrial operations do not face (Ohberg, 2013).

The local food movement faces significant hurdles from economic challenges. Financial burdens affect local food producers through elevated production expenses along with restricted access to both capital and credit while they also encounter limited economies of scale. The nature of local food production requires smaller production scales which lead to increased production costs and decreased profitability when compared to large-scale conventional farming. Local food producers encounter difficulties when attempting to find affordable land and obtain long-term leases which obstructs their ability to create and sustain successful local food businesses (Ohberg, 2013).

The development of the local food movement encounters barriers from social and cultural influences (Bui, 2014). Studies by Campa & Goldberg (2005) point out that consumer awareness about local food products together with their need for convenience and price sensitivity create barriers to local food adoption. A number of consumers remain unaware of local food advantages and they see it as a pricier and less convenient choice compared to traditional options (Galli & Brunori, 2013). The demand for local food products is influenced by cultural norms which show preference toward imported and exotic food items according to Ohberg (2013).

The local food movement faces obstacles because of the necessity for enhanced collaboration and networking between local food stakeholders. The development of a strong local food system depends on collaborative efforts from farmers, consumers, policymakers and additional stakeholders. The progress of the local food movement suffers because key players lack adequate communication and coordination (Ohberg, 2013).

The paper by Maye & Kirwan (2013) demonstrates how AFNs face risks of being co-opted and commercialized which can weaken their unique features and negatively impact their sustainable results.

As with traditional supply chains the SFCS faces specific challenges that require comprehensive understanding and management before it can be effectively proposed as an alternative to existing food supply systems.

2-2-4- Previous research on alternative food networks

The study by Maye & Kirwan (2013) opens with an analysis of alternative food networks which stand apart due to their unique attributes that challenge traditional industrial food systems. The authors emphasize increasing interest in local and sustainable food production and direct relationships between farmers and consumers as well as community-supported agriculture together with farmers' markets and food cooperatives. The emergence of alternative food networks represents an effort to confront the environmental damage and public health risks along with social disparities produced by traditional food systems (Tregear, 2011).

The paper identifies the necessity to tackle power disparities and inequality concerns that exist within Alternative Food Networks (Mount, 2015). The author contends that contemporary studies fail to account for the social interactions and power structures present in Alternative Food Networks which encompass race, gender, class, and ethnicity. Future academic studies need to utilize a critical perspective to investigate power dynamics within Alternative Food Networks and understand their impact on governance structures, participation processes, and outcomes. The paper highlights the importance of placing Alternative Food Networks into broader food system contexts while examining their relationships with various actors and institutions. Alternative Food Networks operate within larger food systems which are affected by global, regional and local factors. The paper advocates for studies that explore how Alternative Food Networks interact with conventional food systems, policy institutions and consumers and the subsequent effects of these interactions on Alternative Food Networks' operations and results (Mount, 2015).

Local food systems governance requires complex coordination across multiple actors, institutions and policies according to the author who highlights that operating scale impacts these systems (Jarosz, 2008).

This study examines the notion of scale and its importance within the governance framework of local food systems. Scale determines the operational size or level of a system while influencing how governance dynamics function. The author maintains that the scale of operation plays a critical role in local food systems governance by influencing stakeholder relationships and the regulatory structures that govern these systems.

The study examines the effect of local food systems scale on their governance frameworks and results. The analysis recognizes three primary local food system scales which include micro-scale, meso-scale and macro-scale. Local food systems at the micro-scale operate through direct producer-consumer relationships exemplified by community-supported agriculture (CSA) and farmers' markets. Meso-scale local food systems operate through networks and cooperatives which bridge producers with consumers throughout broader geographical regions. At the macro-scale level local food systems incorporate regional or statewide programs intended to advance local food production and consumption by means of policy and regulatory frameworks.

The author posits that different scales of local food systems create specific governance structures which affect decision-making processes and power dynamics while shaping institutional arrangements. Micro-scale systems emphasize participatory decision-making with direct producer and consumer involvement while meso-scale and macro-scale systems require more extensive governance structures that include numerous actors and institutions. The scale of operation for local food systems governance affects the achievement of economic viability and environmental sustainability alongside social equity. (Jarosz, 2008)

According to Sonnino and Marsden (2006) the common division between alternative agri-food networks and mainstream agri-food networks simplifies their relationship too much and overlooks the complex network interdependencies and interactions that exist between them. The authors identify various practices and participants that belong to alternative food networks such as organic agriculture, community-supported agriculture, farmers' markets and food cooperatives. The authors demonstrate that these networks show significant diversity across their size, governance structures, objectives and interactions with traditional food networks. The study analyzes how alternative food networks interact with conventional food systems throughout Europe while rejecting the usual dualistic view of these networks. The authors demonstrate that these networks function through interconnections of collaboration and competition which drive their co-evolution instead of existing as isolated separate entities. Alternative food networks depend on conventional networks for their distribution processes and marketing approaches while conventional food networks modify their practices to accommodate shifts in consumer demands according to alternative methodologies (Sonnino & Marsden, 2006).

Goodman (2004) discusses the constraints of SFSCs by pointing out problems related to scalability and accessibility of resources alongside market competition and regulatory barriers. The authors emphasize that policy support, institutional frameworks and stakeholder cooperation are essential to address challenges which will advance the development of SFSCs (Goodman, 2004).

The authors in Tregear (2011) emphasize the crucial role that "alternative" food networks play in shaping food systems because they contribute to building sustainable and resilient food systems.

Mount's 2015 work emphasizes how Alternative Food Networks advance sustainable food systems while tackling food insecurity and boosting local economies.

(Holloway, 2007) explores how alternative food systems function within social and cultural contexts. Alternative food systems help restore local food cultures while building community involvement and advocating for social justice through improved food access and affordability.

The study by Renting et al. (2003) investigates the effects of distance and transport infrastructure along with regional identity on local food supply chain organization and operation within this region. The research paper emphasizes consumer demand as a key factor that stimulates local food retail operations. The authors examine the reasons why consumers select local food products based on their concerns about food safety, health benefits, and sustainability. This study explores retailer responses to consumer demands and details their promotional strategies for local food products (Renting et al., 2003).

2-3- Conventional food supply chains

2-3-1- Overview of the steps in a globalized food supply network

The production and distribution chains of conventional food systems operate on a global scale (Jarosz, 2008). Sonnino & Marsden (2006) explains why conventional food systems attract criticism because of their environmental damage, social inequality effects, erosion of local food customs and health issues which has led to increased interest in different food system approaches according to Goodman (2004).

The food demand fell sharply because of COVID-19 closures of cafes and restaurants along with other hospitality businesses. Price reductions resulted in economic losses for farmers and food value chain stakeholders. The COVID-19 pandemic led to supply chain disruptions which resulted in shipment delays and shortages of essential inputs accompanied by higher transport expenses (Herrera-Araujo et al., 2021).

Japan continues to build its raspberry supply chain which faces substantial production and distribution problems. Main challenges consist of Japan's scarce arable land alongside its divided small-scale farms and weather-related obstacles combined with labor deficits from its aging agricultural workforce. The perishable nature of raspberries requires enhancement of cold chain logistics and distribution networks in Japan while facing competition from less expensive imported raspberries from the U.S. and Mexico. The growing consumer interest in health-focused products such as organic raspberries creates opportunities for local farmers. Subsidies from the government together with advanced farming technologies and farmer cooperative networks could enable Japan to grow its domestic raspberry production and develop a self-reliant supply network (Miyairi et al., 2012).

The COVID-19 pandemic revealed the susceptibility of worldwide supply chains to interruptions due to lockdown measures implemented globally (Wang et al., 2021).

2-3-2- Link with resilience and food security

The coffee sector can adopt multiple approaches to create more resilient value chains. The coffee sector must expand its offerings through the development of alternative crops and products with added value. Alternative agricultural practices enable farmers to generate new income sources while decreasing their dependence on coffee production (Herrera-Araujo et al., 2021).

Stakeholders within the coffee industry have the opportunity to enhance supply chain operations through digital technology implementations which boost efficiency and provide better traceability and transparency. The implementation of these measures will help protect farmers from disruptions while also expanding their access to markets.

Coffee farms require the adoption of sustainable agricultural techniques and climate-smart farming methods to enhance their capacity to withstand climate change. Sustainable agricultural practices can be advanced through agroforestry promotion alongside better water management systems and effective soil conservation techniques.

Public-private partnerships can be formed to assist smallholder farmers through enhanced financial access and improved supply of agricultural inputs and technology. The initiatives may consist of setting up credit programs while offering technical help and market access support. (Herrera-Araujo et al., 2021)

The purpose of this work involves analyzing two networks to enhance our comprehension of their resilience capabilities.

2-3-3- How can we compare the resilience of two supply chains?

Quantitative methods of measuring resilience need to be developed to effectively measure and compare the resilience between two supply networks. Multiple research papers suggest the use of modeling approaches alongside deterministic models, fuzzy probabilistic models and hybrid fuzzy models to achieve this goal (Clavijo-Buritica et al., 2019).

The study by Behzadi et al. (2020) examines quantitative and qualitative metrics for evaluating supply chain resilience which includes aspects of inventory management, transportation, and demand management.

The authors in the paper (Soni et al., 2014) apply a deterministic modeling approach to measure how well supply chains resist and bounce back from disruptions. The researchers introduce a new resilience measurement tool that integrates system performance metrics with recovery time and vulnerability indicators for full supply chain resilience evaluation. The framework evaluates supply chain network resilience by examining factors like demand variability together with lead times and recovery actions.

Chen et al. (2020) introduce a quantitative resilience measure which evaluates supply chain resilience by considering both direct and indirect disruption effects through a comprehensive approach. Supply chains will become more adaptable and robust against disruptions by enhancing decision-making processes in supply chain design as well as risk management and response planning through the proposed measure.

The authors in (Jain et al., 2017) propose a multi-dimensional resilience framework that integrates four key dimensions: operational, informational, behavioral, and financial resilience. The framework presents a complete approach that evaluates supply chain resilience by examining multiple operational elements. The authors create a complete resilience evaluation model that features multiple indicators specific to each resilience dimension. The assessment model utilizes qualitative and quantitative metrics to evaluate supply chain resilience across multiple tiers including the entire supply chain system and specific firm and process levels.

The article by Rajesh R. introduces a fuzzy logic method for examining manufacturing supply chain resilience to provide valuable evaluation methods. The author emphasizes the importance of resilience in current supply chain management operations and recommends utilizing fuzzy logic to evaluate resilience levels. The study examines essential elements that influence supply chain resilience including disruptions and vulnerabilities along with recovery abilities. Through his fuzzy approach the author manages to account for the uncertainties and imprecise data that often occur in supply chain management practices (Rajesh, R. 2019).

A 2017 paper titled "Hybrid fuzzy-probabilistic approach to supply chain resilience assessment" in IEEE Transactions on Engineering Management introduces fundamental concepts for supply chain resilience assessment. Rajesh (2019) presents a unique approach that merges fuzzy logic with probabilistic methods to evaluate supply chain resilience. This paper introduces a hybrid method which merges fuzzy logic, designed to manage uncertain and imprecise information, with probabilistic techniques that employ probability distributions to express uncertainty. By integrating qualitative and quantitative dimensions, this methodology delivers a thorough and robust evaluation of supply chain resilience.

This research evaluates how supply chains maintain their functionality under stress. Various resilience indicators including vulnerability, adaptability and recoverability form the basis of the proposed approach which delivers a comprehensive assessment of supply chain resilience. The research utilizes fuzzy logic as a means to tackle the uncertainty problem in supply chain resilience assessment. Fuzzy logic systems enable representation and manipulation of imprecise information including expert opinions and subjective evaluations that frequently appear in supply chain resilience assessments. The approach allows for realistic and adaptable supply chain resilience evaluations in situations of uncertainty.

The paper integrates probabilistic modeling techniques to represent the random characteristics of supply chain disruption events. Probability distributions and Bayesian networks serve as probabilistic tools to model disruption uncertainties by estimating their likelihood and impact. The approach enables precise evaluation of supply chain resilience through probabilistic metrics which enhances the assessment's objectivity and rigor.

2-4- Previous works on resilience and the research gap

Tsai et al. Tsai et al. (2021) developed a methodology that integrates graph theory with decision-making techniques and fuzzy logic to assess the SCR index. When researchers applied their novel methodology to Taiwan's semiconductor supply chain they discovered it successfully pinpointed crucial nodes and edges that determined supply chain resilience.

Similarly, Tang et al. Tang et al. (2021) developed a graph theory-based method to assess supply chain vulnerability to cyber threats. The authors implemented this method on a Chinese automotive supply chain case study which revealed that it accurately identified the critical nodes and edges susceptible to cyber-attacks. The study demonstrated how their methodology could assess different cybersecurity strategies for strengthening supply chain resilience.

Feng et al. Feng et al. (2021) introduced a graph theory-based method to assess supply chain resilience against natural disaster impacts. The research team used their method on a Chinese food supply chain case study and successfully identified which critical nodes and edges were impacted by natural disasters. The research demonstrated how their methodology could assess the success of various mitigation strategies for strengthening supply chain resilience.

A study by Goyal et al. In 2021 Goyal et al. examined how Indian manufacturing firms adapted their supply chains to address the challenges of the COVID-19 pandemic. Firms responded to the pandemic impact with multiple strategies including higher inventory levels, supplier diversification, and digital technology adoption.

The existing literature lacks examples of how developed quantitative models can measure and compare different supply networks to identify the most resilient network configuration. We chose to expand on existing quantitative models and adjust them for use across different supply network types including short, hybrid, and conventional to evaluate their benefits and shortcomings in comparable situations through their performance numbers.

Chapter 3 Methodology

This study aims to quantitatively compare the resilience of short and long supply chains in the context of raspberry production, focusing on both their cost-efficiency and resilience in the face of disruptions in North Western Territories of Canada. We build on the deterministic cost variables acquired from the studies of Wohlgemuth, D. (2012), and Bolda et al, (2017) to develop our methodology that involves a detailed analysis of the supply networks, from production to consumption, using linear programming model to optimize the movements and costs within these networks.

3-1- Supply Network Decomposition

As the first step, the supply network is broken down into incremental movements, tracking each movement based on the weight of the raspberries being transported. The network encompasses three farms, two processing plants (where raspberries are washed, processed, and packaged), and two consumption zones. This way, the network consisting of nodes that represent farms, plants, and consumption zones, and the arcs that represent the movements between these nodes, is connected in order to quantitatively define the supply chain.

The nodes in question include *Farm 1*, *Farm 2, Farm 3, Plant 1, Plant 2, Consumer zone 1, and Consumer zone 2*. The set of farms is denoted by *I*, plants by *J*, and consumers by *L*. The flows between farms and plants are represented by *X*, and the flows between plants and consumers are denoted by *Y*. Three raspberry types are being produced at each farm, separated based on quality level with *Raspberry 1* being the highest quality. These are introduced to the model under the set *M*.

K represents the transportation mode for the first leg of the network (from farms to processing plants), which includes two vehicle types, and for the second leg (from plants to consumption zones), two other vehicle types are used, which we tag as *k'*. The integer variables *NV1* and *NV2* signify the number of trips servicing the flow from farms to plants and from plants to markets, respectively through the cars *k* and *k'*. A linear programming model governs these movements, aiming to minimize total costs while satisfying the demand at the consumption zones. Costs are deterministic, and movements are the variables in the model.

W refers to the production level, which is planned according to inventory levels signified by *NI*. We have two types of inventories, raw and processed, with the first referring to the raspberries that come from the farms and are stored at the plant, and after going through the processes, they are stored and tracked as processed raspberries.

All these movements and processes happen in the time span of 4 weeks, which is equal to the shelf life of raspberries. We study the supply network in one-week increments, denoted by *t*.

The table below shows the movement and storage variables we just introduced.

Table 3-1 Short Supply Chain Variables

Variable	**Definition**
X_{ijtk}^{m}	The amount in lb of raspberry type m that is transferred from *farm i* to *plant* j with vehicle *k* in time *t*
$Y_{jltk'}^{p}$	The amount in lb of product type *p* that is transferred from plant *j* to consumer *l* with vehicle *k'* in time *t*

$NV_{1_{ijkt}}$	The number of trips between farm *i* and plant *j* with vehicle *k* in time *t*
$NV_{2_{jlk't}}$	The number of trips between plant *j* and consumer *l* with vehicle k' in time *t*
NI_{jt}^{m}	The amount in lb of raspberry type *m* that is stored at plant *j* in time *t*
NI_{jt}^{p}	The amount in lb of product type *p* that is stored at plant *j* in time *t*
W_{jt}^{p}	Production level at plant *j* for product *p* at time *t*

Table 3-2 Short Supply Chain *Parameters*

Parameter	**Definition**
$FarmCap_{it}^{m}$	The maximum amount in lb of raspberry type m that *farm i* is capable of producing in time *t*
$PlantCap_{jt}^{p}$	The maximum amount in lb of raspberry type p that is *plant j* is capable of processing in time *t*
Dem_{lt}^{p}	Total demand for processed raspberry type p in time *t at consumer l*
$StoCap_{j}^{p}$	The storage capacity of processed raspberry type *p* at plant *j*
$StoCap_{j}^{m}$	The storage capacity of raw raspberry type *m* at plant *j*
$NMV1_{ijt}^{k}$	The maximum number of total trips by vehicle *k* in time *t* from farm *i* to plant *j*

$VD1_k$	Total number of available vehicle *k*
$NMV2_{jlt}^{k'}$	The maximum number of total trips by vehicle type *k'* in time *t* from plant *j* customer *l*
$VD2_{k'}$	Total number of available vehicle type *k'*
$CC1_k$	Load capacity of vehicle type *k*
SS_j^m	Safety stock level of raw raspberry type *m* at plant *j*
SS_j^p	Safety stock level of processed raspberry type *p* at plant *j*
$Per1$	Perishability period of raw raspberry type *m*
$Per2$	Perishability period of processed raspberry type *p*
$LotM$	Minimum lot size of raw raspberry type *m*
$LotP$	Minimum lot size of processed raspberry type *p*
$LoadM$	Minimum load limit of raw raspberry type *m*
$LoadP$	Minimum load limit of processed raspberry type *p*
TC_{ijk}	Transportation cost from farm *i* to plant *j* using vehicle *k*
$TC_{jlk'}$	Transportation cost from plant *j* to consumer *l* using vehicle *k'*
hr_{jt}^m	Storage cost of raspberry type *m* in plant *j* during period *t*
hf_{jt}^p	Storage cost of processed raspberry type *p* in plant *j* during period *t*
CPR_i	Production cost at farm *i*
CP_j^p	Proccessing cost at plant *j*
CA_m	Cost of raw materials for raspberry type *m*

3-2- Supply Chain Model

In the short supply chain, all activities are localized within a specific region, minimizing the transportation distances and thereby the associated costs. What sets short supply chains apart from conventional supply chains in our study is the fact that all the food is produced and consumed in the same province. The model includes shipping costs between farms and plants, processing costs at each location, holding costs for both raw and processed raspberries at the plants, and the raw materials cost at each farm.

$$Min(Z) = \sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\sum_{k\in K} TC_{ijk}\, NV1_{ijkt} + \sum_{j\in J}\sum_{l\in L}\sum_{t\in T}\sum_{k'\in K'} TC_{jlk'}\, NV2_{jlk't} +$$

$$\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} hr_{jt}^{m} NI_{jt}^{m} + \sum_{j\in J}\sum_{p\in P}\sum_{t\in T} hf_{jt}^{p} NI_{jt}^{p} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\sum_{k\in K} CPR_i\, X_{ijtk}^{m} +$$

$$\sum_{j\in J}\sum_{p\in P}\sum_{t\in T} CP_j^{p}\, W_{jt}^{p} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\sum_{k\in K} CA_m X_{ijtk}^{m}$$

Subject to:

$$\sum_{j\in J}\sum_{k\in K} X_{ijtk}^{m}\, \beta_{ij} \le \sum_{j\in J} FarmCap_{it}^{m} \quad \forall\, m, i, t \;\ldots\ldots\ldots\ldots \qquad (3.1)$$

$$W_{jt} \le\; PlantCap_{jt}^{p} \quad \forall\, j, t\, , p \;\ldots\ldots\ldots\ldots \qquad (3.2)$$

$$\sum_{j\in J}\sum_{k'\in K} Y_{ijtk'}^{p}\, \alpha_{jl} = \sum_{j\in J} Dem_{lt}^{p} \quad \forall\, p, l, t \;\ldots\ldots\ldots\ldots \qquad (3.3)$$

$$\sum_{p\in P} NI_{jt}^{p}\pi_{jt}^{p} \le \sum_{p\in P} StoCap_{j}^{p} \quad \forall\, j, t \;\ldots\ldots\ldots\ldots \qquad (3.4)$$

$$\sum_{m\in M} NI_{jt}^{m}\, \mu_{jt}^{m} \le\; \sum_{m\in M} StoRaw_{j}^{m} \quad \forall\, j, t \;\ldots\ldots\ldots\ldots \qquad (3.5)$$

$$\sum_{i\in I}\sum_{j\in J} NV1_{ijkt}\beta_{ij} \le \sum_{i\in I}\sum_{j\in J} NMV1_{ijt}^{k} VD1_{k} \quad \forall\, k, t \;\ldots\ldots\ldots \qquad (3.6)$$

$$\sum_{j\in J}\sum_{l\in L} NV2_{jlk't}\alpha_{jl} \le \sum_{j\in J}\sum_{l\in L} NMV2_{jlt}^{k'} VD2_{k'} \quad \forall\, k', t \;\ldots\ldots\ldots \qquad (3.7)$$

$$\sum_{m\in M} X_{ijtk}^{m} \leq CC1_{k} NMV1_{ijkt} \quad \forall\ i,j,t,k \ \ldots\ldots\ldots\ldots \tag{3.8}$$

$$\sum_{p\in P} Y_{jltk'}^{p} \leq CC2_{k'} NMV2_{jlk't} \quad \forall\ j,l,t,k' \ \ldots\ldots\ldots\ldots \tag{3.9}$$

$$\sum_{i\in I} \sum_{j\in J} \sum_{m\in M} \sum_{k\in K} X_{ijtk}^{m} = \sum_{k\in K} CC1_{k} VD1_{k} NMV1_{kt} \quad \forall\ \mathrm{t} \ \ldots\ldots\ldots\ldots \tag{3.10}$$

$$\sum_{j\in J} \sum_{l\in L} \sum_{p\in P} \sum_{k'\in K} Y_{jltk'}^{p} = \sum_{k'\in K} CC2_{k'} VD2_{k'} NMV2_{k't} \quad \forall\ \mathrm{t} \ \ldots\ldots\ldots\ldots \tag{3.11}$$

$$NI_{jt-1}^{m} + \sum_{i\in I} \sum_{k\in K} X_{ijtk}^{m} - \sum_{p\in P} W_{jt}^{p} = NI_{jt}^{m} \quad \forall\ \mathrm{j,t,m} \ \ldots\ldots\ldots\ldots \tag{3.12}$$

$$NI_{jt-1}^{p} + W_{jt}^{p} - \sum_{l\in L} \sum_{k'\in K} Y_{jltk'}^{p} = NI_{jt}^{p} \quad \forall\ \mathrm{j,t,p} \ \ldots\ldots\ldots\ldots \tag{3.13}$$

$$NI_{jt}^{m} \geq SS_{j}^{m} \quad \forall\ \mathrm{m,j,t} \ \ldots\ldots\ldots\ldots \tag{3.14}$$

$$NI_{jt}^{p} \geq SS_{j}^{p} \quad \forall\ \mathrm{p,j,t} \ \ldots\ldots\ldots\ldots \tag{3.15}$$

$$\sum_{t\in T} \mu_{jt}^{m} \leq Per1 \quad \forall\ \mathrm{j,m} \ \ldots\ldots\ldots\ldots \tag{3.16}$$

$$\sum_{t\in T} \pi_{jt}^{p} \leq Per2 \quad \forall\ \mathrm{j,p} \ \ldots\ldots\ldots\ldots \tag{3.17}$$

$$\sum_{j\in J} \sum_{k\in K} \sum_{t\in T} X_{ijtk}^{m} \geq LotM \quad \forall\ \mathrm{i,m} \ \ldots\ldots\ldots\ldots \tag{3.18}$$

$$\sum_{p\in P} \sum_{k'\in K} \sum_{t\in T} Y_{jltk'}^{p} \geq LotP \quad \forall\ \mathrm{j,l} \ \ldots\ldots\ldots\ldots \tag{3.19}$$

$$\sum_{m\in M} \sum_{i\in I} \sum_{j\in J} \sum_{t\in T} X_{ijtk}^{m} \geq LoadM \quad \forall\ \mathrm{k} \ \ldots\ldots\ldots\ldots \tag{3.20}$$

$$\sum_{p\in P} \sum_{j\in J} \sum_{l\in L} \sum_{t\in T} Y_{jltk'}^{p} \geq LoadP \quad \forall\ \mathrm{k} \ \ldots\ldots\ldots\ldots \tag{3.21}$$

$$Con_{j}^{i} * Con_{l}^{j} \leq 1 \quad \forall\ \mathrm{i,j,l} \ \ldots\ldots\ldots\ldots \tag{3.22}$$

$$Avl_{j}^{i} * Avl_{l}^{j} \leq 1 \quad \forall\ \mathrm{i,j,l} \ \ldots\ldots\ldots\ldots \tag{3.23}$$

The costs associated to the processes and moves are described as following:

The objective function comprises of seven factors. These factors are transportation cost from farm to plants, transportation cost from plants to consumers, inventory costs at the plant for raw raspberry, inventory cost of processed raspberry, production costs of raw raspberry at the farms, processing costs of raspberries at plants, cost of raw materials at farms.

The first factor is the transportation cost between farms to the plant. TC_{ijk} is the cost of transportation from farm *i* to plant *j* with vehicle *k,* and when multiplied by $NV1_{ijkt}$ the number of trips, it gives us the total transportation costs from the farms to the plants. The second factor of the objective function is the transportation cost between the plant and customers. $TC_{jlk'}$ represents the cost of transportation from plant j to customer l using vehicle k' and when multiplied by $NV2_{jlk't}$ it returns the total transportation cost of goods from the plants to customers in each time period. Inventory costs at the farm are calculated using hr_{jt}^{m}, which is the inventory cost of grade *m* raspberry in the plant *j,* and when multiplied by the inventory level of raspberry type *m* in plant *j,* NI_{jt}^{m} , returns the cost of inventory in each time period.

The inventory cost of processed raspberries at the plant is the next factor in the objective function. hf_{jt}^{p} is the inventory cost of processed raspberry type *p* in plant *j* and multiplied by NI_{jt}^{p} , the inventory level of that product type in plant *j* during time period *t* accounts for the inventory costs related to the products.

We also take into account the farming expenses of producing raspberries using CPR_i which is the cost of production in farm *i*. When multiplied by the volume of the raspberry type *m* moved out of the farms, $X_{ijtk'}^{m}$ we derive the total production cost at the farm. We can multiply this volume by the unit cost of raw materials, CA_m, to find the total cost of raw materials used in the production and harvesting of raspberry type *m.*

Finally, the processing cost of finished raspberry type p is calculated by multiplying the unit processing cost at plant j, CP_j^p, by the volume processed during the time period *t.*

These movements and processes are governed by the constraints defined below:

The farm and plant capacity constraint is represented by equations (3.2) and (3.3). Constraint 3.2 limits the total production of each raspberry type (1,2,3) at each farm that is sent to plants through transportation modes k to the maximum capacity of the farm.

Constraint (3.3) caps the production level of each product type (1,2,3) at plant *j* during time period *t* to the capacity of that plant.

The demand constraint is represented by constraint (3.4), which guarantees that the demand for each product type at each consumption zone is met through the total amount of product that is shipped from plants to that consumption zone during each time period.

Storage Capacity is represented by Constraint (3.5), ensuring that the inventory level of all processed raspberry types at each plant is bounded by the maximum storage capacity of that plant. Constraint (3.6) does the same for raw raspberry types.

The maximum Number of Trips is governed by constraints (3.7) and (3.8). Constraint (3.7) ensures that the number of trips via the routes that are not affected by disruptions (represented by binary variables α and β) does not exceed the total possible number of trips by that specific vehicle type.

Constraint 8 does the same for vehicle type *k*' that serves plants to consumers.

Load Capacity is reflected in Constraint (3.9) and (3.10). Constraint (3.9) ensures that the total amount of raw raspberry types that is shipped from each farm to each plant through each vehicle type at a certain time period is bounded by the maximum load capacity that the whole fleet of cars can carry.

Constraint (3.10) does the same for each route between plants and consumers.

Flow of product is governed by constraints (3.11) and (3.12). Constraint (3.11) ensures that the flow of raw raspberries from farms to plants is balanced with the total load carried by the fleet of vehicles available between farms and plants.

Constraint (3.12) does the same for the flow of products from plants to consumers.

Balance for unprocessed coffee and processed coffee is monitored using constraints (3.13) and (3.14). Constraint (3.13) ensures that the inventory level at the current time period for each raspberry type m at each plant equals the amount of that raspberry type that was shipped to that plant during the same time period plus all the raspberry that was stored at that plant during the previous time period minus the amount that was processed during that time period.

Constraint (3.14) ensures that the inventory level of each processed raspberry type during the current time period at each plant equals the amount of raspberry that was processed during that time period plus the inventory level of that product from the previous time period minus the amount of that product that gets shipped out to the customers at that time period.

Safety stock level is introduced to the model through constraints (3.15) and (3.16). These ensure that the inventory level of each raspberry type exceeds the safety stock level at each plant during a specific time period. These numbers are calculated based on the demand level at that time.

Perishability of the products is also taken into account using constraint (3.17) and constraint (3.18). Constraint (3.17) ensures that each raw raspberry type is not stored in each plant more than its perishability period. Constraint (3.18) does the same for the product type p at each plant.

Minimum lot size is factored in using constraint (3.19) and (3.20). Constraint (3.19) ensures that the amount of each raw raspberry type that is shipped from farms to plants at a specific time period exceeds the minimum lot size of that product. Constraint (3.20) does the same for each processed raspberry type.

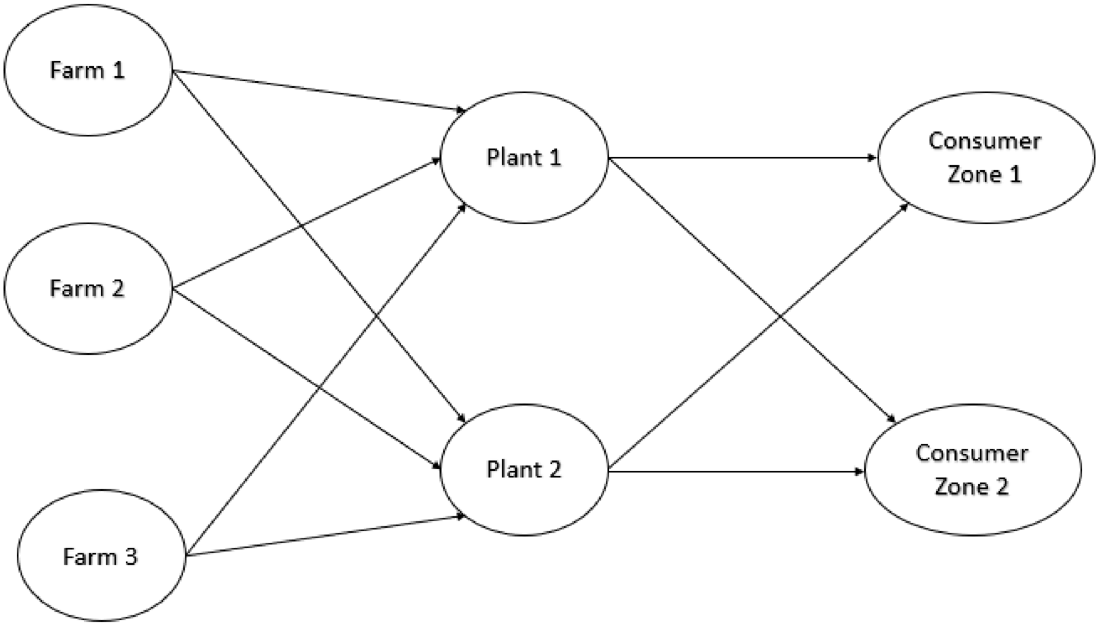
Minimum load is measured in as well by constraint (3.21). Constraint (3.21) ensures that the total amount of raw raspberry that is shipped from farms to plants at a specific time period through each vehicle exceed the minimum load size of that product which is set by the road regulations.

Constraints (3.22) and (3.23) ensure that the maximum availability and connectivity between each node and arc is 100 percent.

The deterministic cost variables used to simulate the supply network were acquired from the studies of Wohlgemuth, D. (2012). Stimulating Commercial Berry Production in the NWT Capital Region. Ecology North and Bolda, M., Tourte, L., Murdock, J., & Sumner, D. A. (2017). Sample Costs to Produce and Harvest Fresh Market Raspberries Primocane Bearing Central Coast Region – Santa Cruz, Monterey, and San Benito Counties. University of California Agriculture and Natural Resources Cooperative Extension and Agricultural Issues Center UC Davis Department of Agricultural and Resource Economics.

Based on the data retrieved from (Agriculture and Agri-Food Canada, 2022), the total demand for raspberries in the northwestern territories of Canada amounts to 4932 kilograms during a 4-week period. (Wohlgemuth, 2017) suggests that in order to produce that number of raspberries, 11 acres of land is needed. We break down this land into three different farms, farm 1 spans six acres, farm 2 three hectares, and farm 3 two acres.

This short supply network is set up in the following format.



3-1 Schematic of the short supply network

Inspired by the work of Clavijo-Buriticá, N., Triana-Sanchez, L., & Escobar, J. W. (Year). A hybrid modeling approach for resilient Agri-supply network design in emerging countries: Colombian coffee supply chain, in order to asses the performance of this short supply network, we study it under a disruption history which is derived from random distribution of said disruptions that intervene with the normal flow of raw and processed raspberries along the arcs of the network. In order for the supply network disruption history to be sufficient in size to capture the significance of disruptions, we simulate 54 unique scenarios and expose our supply network to these disruptions using binary variables α and β. α represents the arcs between the farms and plants, and equals 1 if the arc is functional and 0 otherwise. β represents the arcs between the plants and consumers and equals 1 if the arc is functional and 0 otherwise.

To solve the linear programming model, we code it in Python. Python is a common programming language with numerous libraries that allow us versatility in terms of introducing simulation and conditional variables to a linear programming model. The library we used is called pulp. The code itself is included in the appendix.

To assess the resilience of the supply networks, a disruption history was developed using a random distribution, aligning with the nature of disruptive events that typically fit a normal distribution. Disruptions are integrated into the linear programming model's constraints using binary variables, indicating the functionality of each arc in the supply network. These disruptions are assumed to be resolved after one week, with time steps of one week and a total study span of four weeks. by changing the set of α and β in this program and solving for the optimal cost, we gather the total cost of the supply network for each simulated disruption.

3-3- Conventional Supply Chain Model

For the conventional supply chain, which involves importing raspberries from Mexico, an additional movement through train transportation is included. This introduces a fixed cost to the linear programming model, representing the freight transport and handling costs. The rest of the supply network remains the same, so both supply networks are provided with similar operational environments to be able to compare their performance impartially.

Table 3-3 Conventional Supply Chain Variables

Variable	**Definition**
X_{intk}^{m}	The amount in lb of raspberry type m that is transferred from *farm i* to *Transshipment zone n* with vehicle *k* in time *t*
$Y_{jltk'}^{p}$	The amount in lb of product type *p* that is transferred from plant *j* to consumer *l* with vehicle *k'* in time *t*
$Z_{njtk"}^{m}$	The amount in lb of Raspberry type *m* that is shipped from *Transhipment zone n* to plant *j* with vehicle *k"* in time *t*
$NV_{1_{ijkt}}$	The number of trips between farm *i* and plant *j* with vehicle *k* in time *t*
$NV_{2_{jlk't}}$	The number of trips between plant *j* and consumer *l* with vehicle *k'* in time *t*
NI_{jt}^{m}	The amount in lb of raspberry type *m* that is stored at plant *j* in time *t*
NI_{jt}^{p}	The amount in lb of product type *p* that is stored at plant *j* in time *t*
W_{jt}^{p}	Production level at plant *j* for product *p* at time *t*

Table 3-4 Conventional Supply Chain Parameters

Parameter	**Definition**
$FarmCap_{it}^{m}$	The maximum amount in lb of raspberry type m that *farm i* is capable of producing in time *t*

$PlantCap_{jt}^{p}$	The maximum amount in lb of raspberry type p that is *plant j* is capable of process in time *t*
Dem_{lt}^{p}	Total demand for processed raspberry type p in time *t at consumer l*
$StoCap_{j}^{p}$	The storage capacity of processed raspberry type *p* at plant *j*
$StoCap_{j}^{p}$	The storage capacity of raw raspberry type *m* at plant *j*
$NMV1_{ijt}^{k}$	The maximum number of total trips by vehicle *k* in time *t* from farm *i* to plant *j*
$VD1_{k}$	Total number of available vehicle *k*
$Z_{njtk"}^{m}$	
$NMV2_{jlt}^{k'}$	The maximum number of total trips by vehicle type *k'* in time *t* from plant *j* customer *l*
$VD2_{k'}$	Total number of available vehicle type *k'*
$CC1_{k}$	Load capacity of vehicle type *k*
CTS_{n}	Transshipment cost per lb at port *n*
SS_{j}^{m}	Safety stock level of raw raspberry type *m* at plant *j*
SS_{j}^{p}	Safety stock level of processed raspberry type *p* at plant *j*
$Per1$	Perishability period of raw raspberry type *m*
$Per2$	Perishability period of processed raspberry type *p*
$LotM$	Minimum lot size of raw raspberry type *m*
$LotP$	Minimum lot size of processed raspberry type *p*
$LoadM$	Minimum load limit of raw raspberry type *m*

$LoadP$	Minimum load limit of processed raspberry type *p*

$$Min(Z) = \sum_{i\in I}\sum_{n\in N}\sum_{t\in T}\sum_{k\in K} TC_{ink}\, NV1_{inkt} + \sum_{j\in J}\sum_{l\in L}\sum_{t\in T}\sum_{k'\in K'} TC_{jlk'}\, NV2_{jlk't} +$$

$$\sum_{j\in J}\sum_{m\in M}\sum_{t\in T} hr_{jt}^{m} NI_{jt}^{m} + \sum_{j\in J}\sum_{p\in P}\sum_{t\in T} hf_{jt}^{p} NI_{jt}^{p} + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\sum_{k\in K} CPR_i\, X_{intk}^{m} +$$

$$\sum_{j\in J}\sum_{p\in P}\sum_{t\in T} CP_j^p\, W_{jt}^p + \sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\sum_{k\in K} CA_m X_{intk}^{m} +$$

$$\sum_{j\in J}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\sum_{k"\in K"} CTS_n Z_{njtk"}^{m}$$

Subject to:

$$\sum_{j\in J}\sum_{k\in K} X_{ijtk}^{m}\, \beta_{ij} \le \sum_{j\in J} FarmCap_{it}^{m} \quad \forall\, m, i, t \text{ .... } \quad (3.24)$$

$$W_{jt} \le \; PlantCap_{jt}^{p} \quad \forall\, j, t\, , p \text{ .... } \quad (3.25)$$

$$\sum_{j\in J}\sum_{k'\in K} Y_{ijtk'}^{p}\, \alpha_{jl} = \sum_{j\in J} Dem_{lt}^{p} \quad \forall\, p, l, t \text{ .... } \quad (3.26)$$

$$\sum_{p\in P} NI_{jt}^{p} \pi_{jt}^{p} \le \sum_{p\in P} StoCap_{j}^{p} \quad \forall\, j, t \text{ .... } \quad (3.27)$$

$$\sum_{m\in M} NI_{jt}^{m}\, \mu_{jt}^{m} \le \; \sum_{m\in M} StoRaw_{j}^{m} \quad \forall\, j, t \text{ .... } \quad (3.28)$$

$$\sum_{i\in I}\sum_{j\in J} NV1_{ijkt}\beta_{ij} \le \sum_{i\in I}\sum_{j\in J} NMV1_{ijt}^{k} VD1_{k} \quad \forall\, k, t \text{ .... } \quad (3.29)$$

$$\sum_{j\in J}\sum_{l\in L} NV2_{jlk't}\alpha_{jl} \le \sum_{j\in J}\sum_{l\in L} NMV2_{jlt}^{k'} VD2_{k'} \quad \forall\, k', t \text{ .... } \quad (3.30)$$

$$\sum_{m\in M} X_{ijtk}^{m} \le CC1_{k} NMV1_{ijkt} \quad \forall\; i, j, t, k \text{ .... } \quad (3.31)$$

$$\sum_{p\in P} Y_{jltk'}^{p} \le CC2_{k'} NMV2_{jlk't} \quad \forall\; j, l, t, k' \text{ .... } \quad (3.32)$$

$$\sum_{i\in I}\sum_{j\in J}\sum_{m\in M}\sum_{k\in K} X_{ijtk}^{m} = \sum_{k\in K} CC1_{k} VD1_{k} NMV1_{kt} \quad \forall\, \mathrm{t} \text{ .... } \quad (3.33)$$

$$\sum_{j\in J}\sum_{l\in L}\sum_{p\in P}\sum_{k'\in K} Y_{jltk'}^{p} = \sum_{k'\in K} CC2_{k'}VD2_{k'}NMV2_{k't} \quad \forall\, \mathrm{t} \ \ldots\ldots \qquad (3.34)$$

$$NI_{jt-1}^{m} + \sum_{i\in I}\sum_{k\in K} X_{ijtk}^{m} - \sum_{p\in P} W_{jt}^{p} = NI_{jt}^{m} \quad \forall\, \mathrm{j,t,m} \ \ldots\ldots\ldots\ldots \qquad (3.35)$$

$$NI_{jt-1}^{p} + W_{jt}^{p} - \sum_{l\in L}\sum_{k'\in K} Y_{jltk'}^{p} = NI_{jt}^{p} \quad \forall\, \mathrm{j,t,p} \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.36)$$

$$NI_{jt}^{m} \geq SS_{j}^{m} \quad \forall\, \mathrm{m,j,t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.37)$$

$$NI_{jt}^{p} \geq SS_{j}^{p} \quad \forall\, \mathrm{p,j,t} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.38)$$

$$\sum_{t\in T} \mu_{jt}^{m} \leq Per1 \quad \forall\ \mathrm{j,m} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.37)$$

$$\sum_{t\in T} \pi_{jt}^{p} \leq Per2 \quad \forall\, \mathrm{j,p} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.38)$$

$$\sum_{j\in J}\sum_{k\in K}\sum_{t\in T} X_{ijtk}^{m} \geq LotM \quad \forall\, \mathrm{i,m} \ \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.39)$$

$$\sum_{p\in P}\sum_{k'\in K}\sum_{t\in T} Y_{jltk'}^{p} \geq LotP \quad \forall\, \mathrm{j,l} \ \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.40)$$

$$\sum_{m\in M}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T} X_{ijtk}^{m} \geq LoadM \quad \forall\, \mathrm{k} \ldots\ldots\ldots\ldots\ldots \qquad (3.41)$$

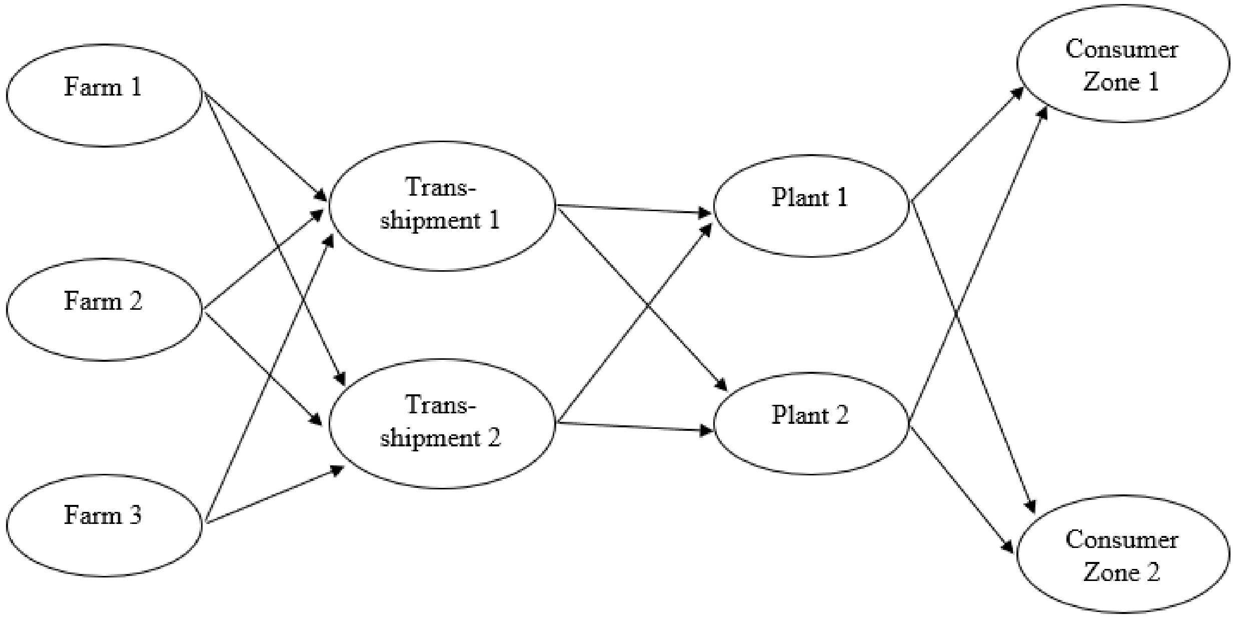
$$\sum_{p\in P}\sum_{j\in J}\sum_{l\in L}\sum_{t\in T} Y_{jltk'}^{p} \geq LoadP \quad \forall\, \mathrm{k} \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.42)$$

$$\sum_{i\in I}\sum_{n\in N}\sum_{m\in M}\sum_{k\in K} X_{intk}^{m} = \sum_{j\in J}\sum_{n\in N}\sum_{m\in M}\sum_{k"\in K"} CTS_{n}Z_{njtk"}^{m} \quad \forall\, \mathrm{t} \qquad (3.43)$$

$$Con_{\ n}^{\ i} * Con_{\ j}^{\ n} * Con_{\ l}^{\ j} \leq 1 \quad \forall\, \mathrm{i,n,j,l} \ \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.44)$$

$$Avl_{\ n}^{\ i} * Avl_{\ j}^{\ n} * Avl_{\ l}^{\ j} \leq 1 \quad \forall\ \mathrm{i,n,j,l} \quad \ldots\ldots\ldots\ldots\ldots\ldots \qquad (3.45)$$

The schematic of the network is as follows:



3-2 Conventional Supply Network Model

To deal with the low visibility on production and operations costs in Mexico so that we can calculate the deterministic costs of our conventional supply chain model we use the method put forward by (Campa & Goldberg, 2005) where import rates are governed by exchange rates, relative fuel rates, relative hourly labour costs, and relative average housing prices [47 & 48]. Through calculation of these relative rates, we get the actual conversion rate between the two countries of Mexico and Canada. This results in the cost tables for our conventional supply network [49,50,51,52] which can be found in Appendix 1.

The other half of the operations that take place in Canada follow the same cost and procedure as the short supply chain.

Now that both supply networks were defined, we need a metric to quantitatively compare the performance of each supply network, in terms of resilience. Such metric was developed combining costs, connectivity, and availability, and is calculated for each disruption scenario (Clavijo-Buriticaet al., 2019). The resilience of the supply chains is compared using the formula *RLS = 1/TC * Con (%) * Avl (%),* where RLS represents Resilience, and TC represents total cost.

Connectivity is calculated for each disrupted network by calculating the ratio of the area of the biggest functional supply network to the whole network. The more resilient the network is the bigger its connectivity would be. For each iteration of α and β the disrupted node or arc is taken off the network and, the ratio of the functioning area to the original area is calculated to derive connectivity. It is calculated using the following formula: *Con (%) =* A_f/A_t where A_f equals the functional area of the network and A_t equals the total area of the network.

Availability is calculated through dividing the number of consumer zones that have access to suppliers by the total number of consumption zones. The higher the availability of a disrupted network the higher its resilience would be. It is calculated using the following formula:

Avl (%)= l_f/l_t where l_f is the number of consumer zones with access to the flow of products and l_t is the total number of consumer zones.

Chapter 4 Numerical Analysis

In order to get a better understanding of the nature of short supply networks, we simulated supply chains with 2,3, 5, 10, 15, 20, and 25 consumer zones. The added complexity to the network gets rid of the natural superiority that short supply networks tend to showcase in smaller networks, providing an impartial environment to compare the performance of each network separately. These networks are later solved in their optimal and disrupted states through the linear programming code we developed. Later, we compare and discuss the underlying reasons for the performance gap between the two networks whenever said gap is remarkable. Building on the operations costs associated with Raspberry production in Canada obtained from Wohlgemuth, D. (2012), the optimized cost of production, storage, and transportation of each network is calculated.

Table 4-1 Cost Parameters

Cost Parameter	Farm 1	Farm 2	Farm 3
Process Cost/lb	4.82	4.1	3.9
Unit Cost of Supply Raspberry type 1/Lb	0.15	0.15	0.15
Unit Cost of Supply Raspberry type 2/Lb	0.12	0.12	0.12
Farm Production Capacity Cap	1762	863	575

Cost Parameter	Plant 1	Plant 2
Process Cost/lb	1	2

Holding Cost Raspberry M/lb	0.19	0.19
Holding Cost Raspberry P/lb	0.21	0.21

Table 4-2 Inventory Variables

Inventory variable	Plant 1	Plant 2
Max Duration of Raw Raspberry Inventory(weeks)	3	3
Max Duration of Processed Inventory(weeks)	2	2
Safety Stock Level Raw at Plant 1	1100	
Safety Stock Level Raw at Plant 2		1000
Safety Stock Level Processed at Plant 1	950	
Safety Stock Level Processed at Plant 2		850
Production Capacity plant	5000	4000
Storage Capacity of raspberry	110950	110950
Demand at Consumption Zone	2000	2300

Table 4-3 Transportation Variables

Transportation variable	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
Number of Available Vehicles	10	15	20	25
Load Capacity of Vehicle k	1296	3000	10000	15000
Minimum Load	1000	1000	1000	1000

Min Lot Size Raw	4.5	4.5	4.5	4.5
Min Lot Size Product	4.5	4.5	4.5	4.5
Maximum Number of Trips Vehicle	28	28	84	84
Shipping Cost Vehicle Type 1 per trip	10	13	15	12
Shipping Cost Vehicle Type 2 per trip	16	17	14	16
Shipping Cost Vehicle Type 3 per trip	10	13	15	12
Shipping Cost Vehicle Type 4 per trip	16	17	14	16

Later, by disrupting each node and arc until we get a significant enough population, disruption scenarios are created, and the costs are calculated again. As an example, in a 5-customer zone network that has 3 farms and 2 plants. To take out the arc connecting plant 2 to consumer 5 ($j = 2$ and $l = 5$) we put $\alpha_{jl} = 0$ into the constraints and solve the linear programming model again in this disrupted scenario. In the case of short supply chains, the model we need to solve for this specific disruption becomes:

$$Min(Z) = \sum_{i\in(1,2,3)} \sum_{j=1} \sum_{t\in T} \sum_{k\in K} TC_{i1k}\, NV1_{i1kt} +$$

$$\sum_{j=1} \sum_{l\in(1,2,3,4)} \sum_{t\in T} \sum_{k'\in K'} TC_{1lk'}\, NV2_{1lk't} + \sum_{j=1} \sum_{m\in M} \sum_{t\in T} hr_{1t}^{m} NI_{1t}^{m} +$$

$$\sum_{j=1} \sum_{p\in P} \sum_{t\in T} hf_{1t}^{p} NI_{1t}^{p} + \sum_{i\in I} \sum_{j=1} \sum_{m\in M} \sum_{t\in T} \sum_{k\in K} CPR_i\, X_{i1tk}^{m} + \sum_{j=1} \sum_{p\in P} \sum_{t\in T} CP_1^p\, W_{1t}^{p} +$$

$$\sum_{i\in I} \sum_{j=1} \sum_{m\in M} \sum_{t\in T} \sum_{k\in K} CA_m X_{i1tk}^{m}$$

Subject to:

$$\sum_{j=1} \sum_{k\in K} X_{i1tk}^{m}\, \beta_{i1} \le \sum_{j\in J} FarmCap_{it}^{m} \quad \forall\, m, i, t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.1}$$

$$W_{1t} \le\; PlantCap_{1t}^{p} \quad j = 1 \;\&\; \forall\, t\,, p \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.2}$$

$$\sum_{k'\in K} Y_{i1tk'}^{p}\, \alpha_{1l} = \sum_{j=1} Dem_{lt}^{p} \quad \forall\, p, l, t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.3}$$

$$\sum_{p\in P} NI_{j=1t}^{p} \pi_{j=1t}^{p} \le \sum_{p\in P} StoCap_{j=1}^{p} \quad \forall\, t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.4}$$

$$\sum_{m\in M} NI_{j=1t}^{m}\, \mu_{j=1t}^{m} \le\; \sum_{m\in M} StoRaw_{j=1}^{m} \quad \forall\, t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.5}$$

$$\sum_{i\in I} NV1_{i1kt} \beta_{ij=1} \le \sum_{i\in I} NMV1_{ij=1t}^{k} VD1_k \quad \forall\, k, t \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.6}$$

$$\sum_{l\in L} NV2_{j=1lk't} \alpha_{j=1l} \le \sum_{l\in L} NMV2_{j=1lt}^{k'} VD2_{k'} \quad \forall\, k', t \;\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.7}$$

$$\sum_{m\in M} X_{ij=1tk}^{m} \le CC1_k NMV1_{ij=1kt} \quad \forall\; i, t, k \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.8}$$

$$\sum_{p\in P} Y_{j=1ltk'}^{p} \le CC2_{k'} NMV2_{j=1lk't} \quad \forall\; l, t, k' \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{4.9}$$

$$\sum_{i\in I} \sum_{m\in M} \sum_{k\in K} X_{ij=1tk}^{m} = \sum_{k\in K} CC1_k VD1_k NMV1_{kt} \quad \forall\, \mathrm{t} \;\ldots\ldots\ldots\ldots\ldots \tag{4.10}$$

$$\sum_{l\in L} \sum_{p\in P} \sum_{k'\in K} Y_{j=1ltk'}^{p} = \sum_{k'\in K} CC2_{k'} VD2_{k'} NMV2_{k't} \quad \forall\, \mathrm{t} \;\ldots\ldots\ldots\ldots \tag{4.11}$$

$$NI_{j=1t-1}^{m} +\; \sum_{i\in I} \sum_{k\in K} X_{ijt=1k}^{m} -\; \sum_{p\in P} W_{j=1t}^{p} =\; NI_{j=1t}^{m} \quad \forall\, \mathrm{t, m} \;\ldots\ldots\ldots \tag{4.12}$$

$$NI^{p}_{j=1t-1} + W^{p}_{j=1t} - \sum_{l\in L}\sum_{k'\in K} Y^{p}_{j=1ltk'} = NI^{p}_{j=1t} \quad \forall \text{ t, p} \ldots\ldots\ldots\ldots \tag{4.13}$$

$$NI^{m}_{j=1t} \geq SS^{m}_{j=1} \quad \forall \text{ m, t} \ldots\ldots\ldots\ldots \tag{4.14}$$

$$NI^{p}_{j=1t} \geq SS^{p}_{j} \quad \forall \text{ p, t} \ldots\ldots\ldots\ldots \tag{4.15}$$

$$\sum_{t\in T} \mu^{m}_{j=1t} \leq Per1 \quad \forall \text{ m} \ldots\ldots\ldots\ldots \tag{4.16}$$

$$\sum_{t\in T} \pi^{p}_{j=1t} \leq Per2 \quad \forall \text{ p} \ldots\ldots\ldots\ldots \tag{4.17}$$

$$\sum_{k\in K}\sum_{t\in T} X^{m}_{ij=1tk} \geq LotM \quad \forall \text{ i, m} \ldots\ldots\ldots\ldots \tag{4.18}$$

$$\sum_{p\in P}\sum_{k'\in K}\sum_{t\in T} Y^{p}_{j=1ltk'} \geq LotP \quad \forall \text{ l} \ldots\ldots\ldots\ldots \tag{4.19}$$

$$\sum_{m\in M}\sum_{i\in I}\sum_{t\in T} X^{m}_{ij=1tk} \geq LoadM \quad \forall \text{ k} \ldots\ldots\ldots\ldots \tag{4.20}$$

$$\sum_{p\in P}\sum_{l\in L}\sum_{t\in T} Y^{p}_{j=1ltk'} \geq LoadP \quad \forall \text{ k} \ldots\ldots\ldots\ldots \tag{4.21}$$

$$Con^{\,i}_{\,j=1} * Con^{\,j=1}_{\,l} \leq 1 \quad \forall \text{ i, l} \ldots\ldots\ldots\ldots \tag{4.22}$$

$$Avl^{\,i}_{\,j=1} * Avl^{\,j=1}_{\,l} \leq 1 \quad \forall \text{ i, l} \ldots\ldots\ldots\ldots \tag{4.23}$$

To achieve a disruption history that is large enough to be representative of all the minor to major disruptions that can occur in a network, 54 unique permutations of α_{jl} and β_{ij} = 0 or 1 are applied against it calculating the cost parameter under the new circumstances each combination exposes the network to. The reason we stopped at 54 permutations is because this was the point where convergance of outcome metrics (total cost and resilience) occurred hence we realized the sample size was large enough.

The connectivity and availability are also calculated. In the end the resilience for each scenario is calculated using costs and the resilience metrics. To compare the performance of these two supply networks we calculate the average resilience and we also highlight the significant disruptions such as port strikes, railway embargoes, and pandemics.

Comparisons are made through the following calculated performance metrics: Total costs, connectivity, availability, and resilience. Total costs include all the costs associated with the production, transportation, and storage of raspberries represented by equation (1). The lower the total cost the more resilient the network would be. Connectivity increases when the portion of the supply network that is functional is bigger. With higher connectivity comes higher resilience. Availability is directly related to resilience as it is equal to the ratio of consumer zones with access to supply zones.

4-1 Resilience, Availability, Connectivity, and Total Costs across disruption scneatios for each consumer setting

After running the Python code for each disruption scenario and calculating the corresponding resilience metrics we obtain the following table for the simplest network, one with two consumer zones.

Table 4-4 Disruption Scenarios and Resilience Results for 2-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	56391.94	100	100	–	57534	100	100	–
1	43070	78	83	1.50313E-05	42554	78.77	83.83	1.552E-05
2	50386	89	83	1.46609E-05	49451	89.32	82.78	1.495E-05
3	47838	89	93	1.73022E-05	48495	88.38	93.19	1.698E-05

4	41611	78	90	1.68704E-05	42413	78.78	90.33	1.678E-05
5	41349	78	90	1.69774E-05	40648	78.19	89.69	1.725E-05
6	51487	89	90	1.55572E-05	52413	88.87	89.11	1.511E-05
7	42493	78	87	1.59696E-05	43507	78	86.91	1.558E-05
8	49467	89	93	1.67324E-05	50891	88.64	93.41	1.627E-05
9	41712	78	87	1.62689E-05	40873	78.15	86.27	1.649E-05
10	49322	89	93	1.67817E-05	50479	88.54	93.5	1.64E-05
11	49355	89	90	1.62294E-05	48253	88.4	90.11	1.651E-05
12	49391	89	90	1.62174E-05	48200	88.6	89.26	1.641E-05
13	56755	100	97	1.70909E-05	55097	99.63	97.78	1.768E-05
14	40612	78	90	1.72857E-05	41171	77.71	89.15	1.683E-05
15	50103	89	90	1.59872E-05	48717	89.43	90.89	1.668E-05
16	49167	88	86	1.53923E-05	50585	88.44	85.8	1.5E-05
17	49066	77	83	1.30253E-05	48141	77.48	83.1	1.337E-05
18	48695	77	86	1.35989E-05	47986	76.82	86.12	1.379E-05
19	48917	77	76	1.19632E-05	49768	76.9	75.42	1.165E-05
20	49128	77	86	1.3479E-05	48027	77.74	86.86	1.406E-05
21	48731	77	86	1.35888E-05	47419	76.65	86.42	1.397E-05
22	43231	66	83	1.26716E-05	44437	65.84	83.53	1.238E-05
23	42920	66	76	1.16869E-05	41674	66.48	75.62	1.206E-05
24	48917	77	83	1.30649E-05	49800	76.34	82.27	1.261E-05
25	48659	77	80	1.26596E-05	47224	76.42	79.64	1.289E-05
26	48916	77	83	1.30652E-05	49724	77.61	82.59	1.289E-05
27	48784	77	80	1.26271E-05	47630	76.37	79.77	1.279E-05
28	54836	88	93	1.49245E-05	55823	87.96	93.08	1.467E-05
29	43231	66	83	1.26716E-05	42715	65.8	83.28	1.283E-05
30	54587	88	86	1.38641E-05	53340	87.69	86.21	1.417E-05
31	54733	88	86	1.38271E-05	55499	88.09	85.71	1.36E-05

32	48558	77	76	1.20516E-05	47545	77.34	75.78	1.233E-05
33	54798	88	90	1.44532E-05	55717	88.45	90.53	1.437E-05
34	49352	77	86	1.34179E-05	50629	77.65	85.28	1.308E-05
35	48977	77	83	1.3049E-05	49669	76.31	83.65	1.285E-05
36	43471	66	83	1.26014E-05	44070	65.61	82.31	1.225E-05
37	48874	77	90	1.41792E-05	49556	76.63	89.93	1.391E-05
38	55101	88	83	1.32557E-05	55922	88.69	83.14	1.319E-05
39	48537	77	83	1.31674E-05	47786	77.15	82.82	1.337E-05
40	54776	88	90	1.44588E-05	54037	87.84	90.88	1.477E-05
41	55101	88	83	1.32557E-05	54442	87.16	83.77	1.341E-05
42	54836	88	93	1.49245E-05	53636	87.78	92.71	1.517E-05
43	48514	77	86	1.36497E-05	49614	76.85	86.15	1.334E-05
44	49106	77	86	1.3485E-05	48246	77.47	86.05	1.382E-05
45	54732	88	86	1.38273E-05	53902	87.85	86.57	1.411E-05
46	48783	77	76	1.19959E-05	49377	76.46	75.83	1.174E-05
47	48961	77	90	1.4154E-05	50107	76.59	90.59	1.385E-05
48	54857	88	86	1.37959E-05	53401	87.71	86.6	1.422E-05
49	55098	88	83	1.32564E-05	53487	88.16	83.18	1.371E-05
50	48808	77	86	1.35673E-05	48183	76.73	86.43	1.376E-05
51	48765	77	90	1.4211E-05	47430	76.5	90.4	1.458E-05
52	42819	66	80	1.2331E-05	43823	65.36	80.73	1.204E-05
53	55179	88	93	1.48316E-05	54066	88.2	92.77	1.513E-05
54	48575	77	83	1.31571E-05	49380	77.15	83	1.297E-05

Table 4-5 Disruption Scenarios and Resilience Results for 3-consumer zone networks

	Short Supply Network	**Long Supply Network**

Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	58655	100	100	–	57843	100	100	–
1	44041	78.84	84.39	1.5107E-05	45325	79.58	84.82	1.48925E-05
2	51554	90.21	82.05	1.7013E-05	52208	91.07	82.39	1.6944E-05
3	48636	89.26	92.66	2.0726E-05	49370	89.97	92.33	2.04224E-05
4	42371	78.81	90.72	1.8211E-05	41182	78.16	90.85	1.86748E-05
5	42495	77.43	89.25	1.7926E-05	43087	77.6	89.42	1.77264E-05
6	52444	89.17	88.37	1.6835E-05	51158	89.03	89.15	1.73504E-05
7	43322	78.32	86.41	1.7677E-05	42025	78.8	86.88	1.82734E-05
8	50895	88.38	92.54	1.8597E-05	52262	88.18	92.22	1.79096E-05
9	42683	78.62	87.1	1.7337E-05	43841	78	86.48	1.66843E-05
10	50139	89.22	94.32	1.927E-05	48965	88.76	94.92	1.98964E-05
11	50526	88.58	90.18	1.6762E-05	49452	89.46	90.31	1.72115E-05
12	50186	89.14	89.68	1.7663E-05	51174	89.21	89.45	1.72667E-05
13	57649	100	97.19	1.8799E-05	56834	99.2	96.52	1.88337E-05
14	41649	77.72	89.42	1.7169E-05	41066	77.36	89.08	1.73861E-05
15	51593	89.38	91.29	1.7686E-05	52483	89.08	91.52	1.7438E-05
16	50298	88.1	86.49	1.6595E-05	51004	87.89	86.11	1.62133E-05
17	50001	76.77	83.29	1.4785E-05	48523	76.39	83.68	1.52987E-05
18	49519	76.49	86.54	1.6049E-05	50135	77.01	86.08	1.58011E-05
19	49480	76.75	75.89	1.3602E-05	48264	76.95	75.99	1.40748E-05
20	49977	77.72	87.38	1.7906E-05	49143	78.05	88.07	1.8407E-05
21	49575	76.11	87.21	1.5323E-05	50287	75.71	86.49	1.47854E-05
22	44320	65.26	84.27	1.4228E-05	45163	65.43	83.77	1.40318E-05
23	43835	66.74	74.87	1.3527E-05	44455	67.32	74.41	1.34514E-05
24	49785	76.8	82.67	1.7033E-05	48968	77.16	82.28	1.74238E-05
25	49988	76.66	79.16	1.4685E-05	48959	77.21	79.82	1.52988E-05
26	49735	77.45	82.66	1.6261E-05	50814	76.87	83.03	1.57361E-05

27	49649	76.13	79.94	1.4829E-05	50971	76.37	80.47	1.45211E-05
28	56155	88.59	92.37	1.8229E-05	56735	89.05	92.43	1.80285E-05
29	44376	65.24	82.76	1.3172E-05	43312	65.86	83.13	1.36761E-05
30	56182	88.09	86.88	1.646E-05	54883	87.78	86.96	1.67308E-05
31	56149	88.8	85.04	1.548E-05	54774	87.99	84.85	1.56744E-05
32	49110	77.29	75.82	1.4032E-05	47647	76.81	76.02	1.44429E-05
33	55673	87.72	90.78	1.8865E-05	56507	88.08	89.88	1.84293E-05
34	50224	77.73	85.27	1.4537E-05	51511	78.08	84.5	1.42507E-05
35	50007	75.79	83.42	1.4827E-05	51210	75.3	82.83	1.44135E-05
36	44269	65.74	83.09	1.4791E-05	45101	65.66	83.2	1.46234E-05
37	49898	77.38	90.7	1.6928E-05	50471	77.67	90.5	1.67392E-05
38	56588	87.95	83.24	1.4264E-05	57716	87.42	83.8	1.40253E-05
39	49738	77.2	82.84	1.5447E-05	50286	76.99	82.65	1.51002E-05
40	55742	88.22	90.53	1.7296E-05	56826	88.2	90.38	1.69727E-05
41	55911	87.71	84.07	1.4568E-05	54239	87.55	83.99	1.50002E-05
42	55549	87.76	92.43	1.737E-05	56818	88.09	92.17	1.70138E-05
43	49477	77.38	86.41	1.4621E-05	48266	77.23	86.41	1.50011E-05
44	50309	77.32	85.98	1.5292E-05	49507	76.99	85.87	1.54541E-05
45	56324	87.93	86.13	1.5639E-05	54724	88.28	85.71	1.61019E-05
46	49318	75.92	75.25	1.3449E-05	50273	75.18	75.37	1.31502E-05
47	49569	76.48	90.99	1.8656E-05	50913	76.13	91.23	1.80993E-05
48	55776	87.44	86.56	1.4914E-05	54612	87.29	85.99	1.50656E-05
49	55794	88.95	84.01	1.5473E-05	54301	89.75	84.14	1.61727E-05
50	49821	76.97	86.89	1.5979E-05	50462	77.5	86.89	1.58602E-05
51	50093	76.45	91.16	1.6012E-05	49142	76.49	90.51	1.62135E-05
52	43978	65.42	80.46	1.313E-05	42821	65.99	79.66	1.35632E-05
53	56790	88.95	93.05	1.8114E-05	55569	88.55	93.03	1.86097E-05
54	49633	77.33	82.93	1.3886E-05	48984	76.65	82.3	1.38433E-05

Table 4-6 Disruption Scenarios and Resilience Results for 5-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	58616	100	100		60026	100	100	
1	46383	80.19	84.18	1.45536E-05	45682	80.33	83.56	1.46936E-05
2	52857	91.42	81.64	1.41203E-05	52085	92.11	81.34	1.43846E-05
3	50515	90.34	91.74	1.64066E-05	49402	90.87	91.05	1.67477E-05
4	42019	78.29	90.09	1.67858E-05	42814	78.74	89.98	1.65482E-05
5	43742	78.08	90.28	1.61151E-05	42974	78.51	91	1.66251E-05
6	52363	88.76	89.16	1.51134E-05	51154	87.93	89.78	1.54327E-05
7	42524	78.75	87.44	1.61929E-05	43274	79.38	86.88	1.59368E-05
8	53791	87.93	92.78	1.51665E-05	55291	87.95	92.91	1.47789E-05
9	44816	78.43	86.07	1.50626E-05	46155	78.68	85.31	1.45426E-05
10	49595	88.9	94.04	1.68569E-05	49009	88.07	94.12	1.69136E-05
11	50051	88.62	89.61	1.58662E-05	50953	89.23	88.91	1.557E-05
12	51762	89.59	89.07	1.54164E-05	52468	89.26	88.36	1.5032E-05
13	58149	98.91	95.57	1.62563E-05	57052	99.82	94.81	1.65883E-05
14	42166	77.64	89.79	1.65328E-05	42824	76.94	88.9	1.59721E-05
15	53215	88.91	92.2	1.54046E-05	51843	89.37	93.04	1.60387E-05
16	52440	87.98	85.44	1.43344E-05	53416	87.98	84.67	1.39457E-05
17	49272	76.98	82.93	1.29564E-05	48477	77.66	82.69	1.32469E-05
18	51476	77.54	85.78	1.29214E-05	50329	78.25	86.45	1.3441E-05
19	49629	77.1	75.5	1.17292E-05	49028	76.47	75.37	1.17555E-05
20	50410	77.92	88.56	1.36889E-05	51352	77.94	87.73	1.33152E-05
21	51450	75.29	87.11	1.27472E-05	50620	75.98	87.58	1.31456E-05
22	46460	65.6	84.49	1.19297E-05	47294	65.81	83.71	1.16483E-05
23	45205	67.03	73.69	1.09268E-05	44490	67.02	73.14	1.10179E-05
24	49751	77.28	82.12	1.27561E-05	50501	77.98	81.87	1.26418E-05

25	50281	76.45	80.48	1.22366E-05	51311	77.04	80.92	1.21496E-05
26	51933	76.41	82.85	1.219E-05	53396	77.01	83.21	1.20009E-05
27	51495	76.9	80.14	1.19677E-05	52392	76.24	80.38	1.16968E-05
28	58063	88.51	92.36	1.40791E-05	56702	87.67	93.12	1.43977E-05
29	44530	65.64	82.52	1.21638E-05	45618	66.12	82.22	1.19172E-05
30	55908	87.02	87.32	1.35912E-05	54384	86.66	87.1	1.38792E-05
31	55780	88.4	84.89	1.34533E-05	54439	88.03	84.07	1.35946E-05
32	48497	76.94	76.23	1.20938E-05	47506	76.67	76.62	1.23656E-05
33	57345	88.55	90.42	1.39624E-05	57941	88.16	91.03	1.38506E-05
34	52585	77.83	84.98	1.25778E-05	51289	78.58	84.25	1.29081E-05
35	52042	75.59	82.48	1.198E-05	52777	75.61	83.26	1.19282E-05
36	45659	65.67	83.19	1.1965E-05	44640	65.52	83.73	1.22894E-05
37	51081	77.12	89.77	1.35532E-05	52358	77.08	89.42	1.31642E-05
38	58971	87.45	83.26	1.2347E-05	57662	86.69	83.81	1.26001E-05
39	51123	76.66	82.39	1.23545E-05	50472	76.26	82.95	1.25333E-05
40	58040	87.98	89.84	1.36185E-05	59664	88.27	89.61	1.32574E-05
41	55301	88.37	83.15	1.32872E-05	54224	88.3	83.4	1.35811E-05
42	58290	88.37	91.96	1.39415E-05	59312	88.76	91.08	1.36301E-05
43	49172	77.84	87.15	1.3796E-05	48277	77.14	87.14	1.39238E-05
44	50571	76.68	85.67	1.29899E-05	49846	77.09	85.87	1.32803E-05
45	55419	88.44	85.17	1.35917E-05	56184	88.76	85.75	1.35468E-05
46	51655	74.74	75.96	1.09907E-05	50639	74.81	76.11	1.12439E-05
47	52332	75.38	91.63	1.31986E-05	53348	76	91.93	1.30963E-05
48	55750	86.45	85.91	1.33218E-05	57160	86.98	85.61	1.30272E-05
49	55285	90.35	83.76	1.36885E-05	54728	90.44	83.75	1.38401E-05
50	51452	76.94	86.95	1.30023E-05	50611	76.4	86.88	1.31151E-05
51	49848	76.41	90.02	1.37987E-05	48550	76.48	89.46	1.40926E-05
52	43954	65.34	79.7	1.18479E-05	44468	65.64	80.45	1.18754E-05

53	56393	89.08	93.89	1.48311E-05	57178	88.63	94.31	1.46188E-05
54	50102	76.66	82.74	1.26598E-05	50893	77.42	82.69	1.2579E-05

Table 4-7 Disruption Scenarios and Resilience Results for 10-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	61471	100	100		62832	100	100	
1	46368	81.47	85.34	1.49944E-05	47071	83.44	87.1	1.54398E-05
2	53272	93.57	82.96	1.45715E-05	54988	94.63	84.77	1.45883E-05
3	50449	91.95	88.52	1.61341E-05	53187	89.79	86.98	1.4684E-05
4	43253	79.94	87.36	1.61457E-05	44160	81.57	89.87	1.66003E-05
5	44232	77.67	93.61	1.64375E-05	44918	79.1	95.4	1.68E-05
6	52320	89.23	91.88	1.56698E-05	55639	87.42	93.61	1.4708E-05
7	44453	80.66	88.43	1.60456E-05	44508	82.48	86.46	1.60225E-05
8	56503	90.39	90.72	1.45129E-05	60211	92.94	91.92	1.41886E-05
9	47325	80.33	84.26	1.43024E-05	49830	78.46	85.56	1.34719E-05
10	49771	89.04	96.63	1.72871E-05	50614	90.36	99.26	1.77207E-05
11	52092	86.69	90.28	1.50242E-05	54143	88.32	89.34	1.45733E-05
12	53161	91.23	90.86	1.55925E-05	54947	89.26	93.03	1.51126E-05
13	58168	100	97.12	1.66963E-05	60082	100	94.5	1.57285E-05
14	43575	77.85	91.18	1.62898E-05	44006	77.07	92.23	1.61526E-05
15	53297	88.37	90.35	1.49807E-05	56384	86.27	88.11	1.34812E-05
16	53998	86.39	83.79	1.34053E-05	56444	88.92	84.71	1.3345E-05
17	49882	79.24	83.65	1.32883E-05	53815	78.45	85.67	1.24888E-05
18	51372	77.2	88.14	1.32453E-05	52748	78.99	89.62	1.34207E-05
19	50294	77.39	76.69	1.18006E-05	52922	78.98	75.44	1.12586E-05
20	52843	77.03	88.86	1.29531E-05	53422	76.18	87.84	1.25261E-05

21	52111	78.21	89.99	1.35059E-05	55200	76.77	91.91	1.27825E-05
22	47986	64.27	84.59	1.13296E-05	50894	65.19	83.73	1.07249E-05
23	45207	65.71	74.2	1.07853E-05	48114	66.47	76.41	1.0556E-05
24	51966	76.25	83.76	1.22901E-05	52756	75.44	81.37	1.16357E-05
25	52849	79.15	78.74	1.17925E-05	56153	80.04	80.18	1.14288E-05
26	54003	75.54	85.38	1.1943E-05	56407	77.15	87.85	1.20156E-05
27	52995	78.38	81.82	1.21012E-05	56658	80.54	84.24	1.19749E-05
28	57329	85.55	94.76	1.41407E-05	60957	88.08	96.34	1.39206E-05
29	46242	64.51	80.99	1.12985E-05	47408	62.71	82.96	1.09738E-05
30	55713	85.22	89.44	1.36809E-05	57810	86.82	90.62	1.36094E-05
31	54984	86.95	85.62	1.35397E-05	56760	88.76	84.37	1.31935E-05
32	48248	78.03	74.85	1.21053E-05	48093	76.03	74.04	1.1705E-05
33	59161	86.8	93.69	1.37461E-05	63125	88.59	91.3	1.28131E-05
34	52808	77.46	86.73	1.27218E-05	54388	76.41	85.76	1.20484E-05
35	53462	73.61	84.9	1.16896E-05	55876	75.5	86.35	1.16676E-05
36	45720	64.63	85.76	1.2123E-05	46680	66.37	83.76	1.19092E-05
37	53575	76.13	86.84	1.234E-05	55332	75.08	84.94	1.15255E-05
38	58531	88.22	81.66	1.2308E-05	59721	87.26	82.77	1.20937E-05
39	51579	77.65	84.72	1.27544E-05	54759	75.92	82.7	1.14659E-05
40	60904	90.22	87.42	1.29499E-05	62929	92	85.34	1.24765E-05
41	55296	87.12	81.08	1.27742E-05	56586	85.23	82.02	1.23538E-05
42	60401	86.16	90.07	1.28482E-05	61286	87.18	88.36	1.25693E-05
43	49079	75.77	86	1.32769E-05	49881	74.18	88.31	1.31329E-05
44	51306	78.39	84.74	1.29475E-05	51668	76.52	83.29	1.23353E-05
45	57473	89.67	87.99	1.37283E-05	58146	90.89	90.57	1.41573E-05
46	52130	73.32	74.2	1.04362E-05	53377	75.12	72.59	1.02159E-05
47	54162	78.21	89.73	1.2957E-05	55717	77.05	87.21	1.20601E-05
48	58285	84.53	83.57	1.212E-05	59650	86.14	82.6	1.19283E-05

49	56366	92.47	86.21	1.41429E-05	56856	94.08	84.15	1.39244E-05
50	51486	74.25	88.16	1.27138E-05	53369	76.04	89.5	1.2752E-05
51	49223	77.59	90.64	1.42875E-05	52430	76.41	88.31	1.287E-05
52	45775	67.19	79.03	1.16003E-05	48394	67.88	78.2	1.09688E-05
53	58423	89.94	93.27	1.43586E-05	61219	91.16	95.18	1.4173E-05
54	51886	76.6	81.54	1.20378E-05	54809	74.76	80.49	1.09789E-05

Table 4-8 Disruption Scenarios and Resilience Results for 15-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	64522	100	100		62778	100	100	
1	46361	85.21	88.85	1.63305E-05	46257	83.36	89.74	1.61721E-05
2	53147	92.45	82.41	1.43354E-05	55248	94.48	83.78	1.43272E-05
3	52041	87.81	85.33	1.4398E-05	51618	89.69	87.64	1.52282E-05
4	43206	79.36	87.85	1.6136E-05	44753	80.17	89.6	1.6051E-05
5	44562	81.44	93.29	1.70495E-05	46095	83.21	95.03	1.71548E-05
6	53870	88.56	92.63	1.5228E-05	53322	91.02	93.97	1.60406E-05
7	44511	80.19	88.61	1.59639E-05	46543	81.65	89.64	1.57255E-05
8	58736	94.67	93.2	1.50219E-05	60873	96.31	91.92	1.45431E-05
9	48510	80.71	87.83	1.46131E-05	48193	78.85	89.05	1.45696E-05
10	49517	88.46	100	1.78647E-05	52184	86.61	98.28	1.63115E-05
11	52299	85.72	86.83	1.42317E-05	54108	87.22	85.28	1.37467E-05
12	53759	90.5	92.03	1.54926E-05	53005	88.89	93.34	1.56533E-05
13	58153	98.95	92.95	1.58159E-05	61344	100	91.6	1.49321E-05
14	43187	78.59	93.91	1.70896E-05	42728	80.54	95.76	1.80502E-05
15	55752	87.49	90.39	1.41847E-05	58742	85.03	88.37	1.27917E-05
16	56411	87.98	86.41	1.34766E-05	58304	88.87	84.36	1.28585E-05

17	52426	79.87	84.73	1.29083E-05	54636	81.93	83.08	1.24583E-05
18	51822	77.86	88.69	1.33251E-05	54512	80.17	87.02	1.27978E-05
19	52380	80.26	77.16	1.1823E-05	54732	79.01	79.23	1.14374E-05
20	52597	75.31	86.8	1.24283E-05	54800	73.53	87.96	1.18024E-05
21	54747	77.85	89.96	1.27922E-05	54960	80.05	88.52	1.28931E-05
22	50241	64.51	85.22	1.09424E-05	52938	65.16	82.75	1.01855E-05
23	47357	64.8	74.57	1.02036E-05	49023	63.32	73.26	9.46252E-06
24	52156	74.49	79.15	1.13043E-05	51501	75.92	81.04	1.19465E-05
25	54318	78.17	82.33	1.18482E-05	55957	79.6	80.89	1.15068E-05
26	56111	75.75	89.92	1.21392E-05	59293	74.89	92.05	1.16264E-05
27	54656	78.71	82.43	1.18707E-05	54700	79.55	83.29	1.21128E-05
28	58818	89.5	98.42	1.4976E-05	58617	88.43	96.45	1.45505E-05
29	46502	63.64	81.34	1.11318E-05	46684	64.65	79.67	1.1033E-05
30	55682	89.27	88.67	1.42157E-05	55691	90.64	86.23	1.40344E-05
31	55512	87.49	83.51	1.31616E-05	55137	85.69	84.68	1.31603E-05
32	47539	73.8	76.17	1.18248E-05	47379	75.66	74.05	1.1825E-05
33	61510	91.06	88.7	1.31313E-05	64478	88.38	90.04	1.23418E-05
34	53300	74.52	86.81	1.21371E-05	55707	76.19	88.68	1.21287E-05
35	53706	76.56	88.23	1.25776E-05	54346	77.89	85.9	1.23114E-05
36	45985	67.28	82.71	1.21012E-05	48193	66.18	84.73	1.16353E-05
37	53413	76.63	83.85	1.20298E-05	55357	78.82	85.74	1.2208E-05
38	58691	85.81	81.41	1.19027E-05	60593	84.41	82.41	1.14803E-05
39	53787	77.81	81.06	1.17265E-05	55616	80.13	83.1	1.19729E-05
40	61269	90.39	86.96	1.28291E-05	60741	88.74	89.05	1.30099E-05
41	55174	86.27	84.12	1.3153E-05	54507	87.47	85.58	1.37334E-05
42	59789	85.75	86.25	1.23701E-05	60566	84.11	83.86	1.1646E-05
43	48823	75.98	90.17	1.40325E-05	51275	75.02	91.39	1.33711E-05
44	51099	77.56	84.24	1.27862E-05	53927	78.6	82.61	1.20405E-05

45	57160	92.01	92.11	1.48268E-05	57500	92.95	90.89	1.46925E-05
46	52069	76.91	70.62	1.04312E-05	54126	75.02	72.68	1.00737E-05
47	54288	75.55	85.78	1.19375E-05	56402	74.35	84.46	1.11336E-05
48	57405	84.98	81.24	1.20265E-05	58277	86.49	79.15	1.17469E-05
49	55881	95.32	83.31	1.42109E-05	58256	97.22	84.61	1.412E-05
50	52032	78.22	87.86	1.32081E-05	51428	79.17	86.43	1.33053E-05
51	51664	77.53	86.14	1.29266E-05	51386	78.37	88.67	1.35233E-05
52	47993	65.89	77.35	1.06194E-05	48024	67.56	75.64	1.06409E-05
53	60086	88.73	93.75	1.38442E-05	60085	91.04	96.08	1.45578E-05
54	53822	73.46	82.39	1.12451E-05	53360	74.57	83.32	1.1644E-05

Table 4-9 Disruption Scenarios and Resilience Results for 20-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	65451	100	100		64303	100	100	
1	47457	81.02	90.89	1.55169E-05	46601	82.34	93.39	1.65013E-05
2	56390	95.67	85.98	1.45872E-05	54854	94.22	83.45	1.43337E-05
3	53264	90.97	86.08	1.47016E-05	51904	89.54	88.46	1.52602E-05
4	46531	78.87	88.54	1.50076E-05	45428	77.49	90.91	1.55074E-05
5	47059	82.16	96.52	1.68512E-05	46347	80.18	98.22	1.69919E-05
6	53922	92.97	96.12	1.65726E-05	53737	91.94	93.71	1.60331E-05
7	47225	79.35	87.83	1.47576E-05	46250	78.16	86.25	1.45758E-05
8	62041	93.56	89.18	1.34486E-05	60820	91.42	90.1	1.35432E-05
9	49079	76.73	86.49	1.35219E-05	48599	77.5	85.31	1.36042E-05
10	52739	87.81	96.07	1.59957E-05	51653	86.62	93.57	1.56913E-05
11	55267	85.51	87.67	1.35645E-05	54357	83.3	89.43	1.37048E-05
12	54583	90.35	90.62	1.5E-05	53029	88.45	89.58	1.49414E-05

13	62512	97.61	89.57	1.3986E-05	60435	98.73	91.95	1.50215E-05
14	44062	78.13	98.62	1.74873E-05	42807	78.94	96.96	1.78803E-05
15	59526	82.92	86.68	1.20745E-05	58228	81.57	85.31	1.19509E-05
16	59774	91.48	83.43	1.27683E-05	58633	94.16	85.11	1.36679E-05
17	54367	79.78	80.78	1.18539E-05	54661	78.64	83.05	1.19483E-05
18	55793	82.14	88.36	1.30086E-05	54047	81.2	86.49	1.29941E-05
19	54477	80.41	77.69	1.14672E-05	54118	81.95	75.37	1.14131E-05
20	56429	75.05	86.08	1.14486E-05	54655	74.23	87.8	1.19246E-05
21	55249	78.91	87.49	1.2496E-05	54072	77.94	89.58	1.29121E-05
22	54347	66.97	84.88	1.04594E-05	53017	66.09	86.23	1.07493E-05
23	50606	62.08	72.52	8.89617E-06	48650	61.08	70.63	8.86761E-06
24	53526	74.47	80.01	1.11318E-05	52357	76.62	81.38	1.19093E-05
25	56988	80.9	78.51	1.11453E-05	56585	81.78	80.73	1.16675E-05
26	60593	77.11	93.61	1.19128E-05	58255	75.64	94.79	1.23079E-05
27	56430	77.95	84.52	1.16753E-05	54889	76.19	83.06	1.15294E-05
28	58632	89.74	94.26	1.4427E-05	57971	91.61	91.7	1.44911E-05
29	46422	65.82	81.08	1.1496E-05	46196	64.15	82.38	1.14398E-05
30	56472	92.49	88.79	1.45421E-05	55570	94.92	86.61	1.47941E-05
31	56836	84.05	86.31	1.27637E-05	55185	81.94	88.81	1.31867E-05
32	48756	77.41	72.02	1.14346E-05	47347	75.2	73.76	1.17152E-05
33	65672	89.31	92.73	1.26108E-05	64321	87.2	94.44	1.28032E-05
34	56206	78.06	86.37	1.19952E-05	54965	78.98	84.22	1.21016E-05
35	55250	79.11	83.8	1.19989E-05	53912	77.45	81.96	1.17744E-05
36	48299	65.48	85.92	1.16483E-05	48477	66.17	87.84	1.19899E-05
37	57400	76.69	86.65	1.15769E-05	56265	78.88	84.61	1.18619E-05
38	61959	86.71	80.64	1.12854E-05	60781	89.25	81.91	1.20275E-05
39	56543	82.26	85.02	1.23688E-05	55667	83.69	83.05	1.24858E-05
40	61880	86.55	91.65	1.28189E-05	60601	85.54	90.22	1.27349E-05

41	55419	86.23	88.04	1.36986E-05	54855	87.27	87.07	1.38522E-05
42	60627	82.43	81.9	1.11353E-05	59650	80.95	83.93	1.139E-05
43	51791	76.55	92.6	1.36868E-05	51340	77.7	91.03	1.37768E-05
44	54556	79.86	84.98	1.24394E-05	53934	77.47	83.72	1.20254E-05
45	57729	90.26	88.5	1.3837E-05	57282	92.52	90.8	1.46658E-05
46	53845	73.24	74.56	1.01416E-05	54176	75.34	73.34	1.01991E-05
47	56356	72.58	81.99	1.05594E-05	55870	74.6	83.83	1.11933E-05
48	59825	88.25	81.32	1.19959E-05	58130	89.88	82.59	1.27699E-05
49	59096	99.42	86.75	1.45945E-05	58563	97.02	89.06	1.47544E-05
50	52757	81.39	85.04	1.31194E-05	51679	79.71	83.76	1.29192E-05
51	52032	79.42	91.21	1.39221E-05	51651	77.95	88.95	1.34241E-05
52	48835	69.34	74.62	1.05952E-05	48236	70.53	75.44	1.10308E-05
53	62087	93.69	95.09	1.43493E-05	60304	95.69	96.28	1.52776E-05
54	55061	75.63	82	1.12633E-05	53989	73.67	84.16	1.1484E-05

Table 4-10 Disruption Scenarios and Resilience Results for 25-consumer zone networks

	Short Supply Network				**Long Supply Network**			
Scenario	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
Base	66338	100	100		64990	100	100	
1	50506	83.7	94.54	1.56675E-05	46151	85	92	1.69444E-05
2	60161	92.23	84.75	1.29927E-05	55241	93.74	83.5	1.41694E-05
3	55496	87.29	89.59	1.40916E-05	54048	86	91.2	1.45116E-05
4	50106	76.4	93.09	1.4194E-05	46203	75.31	90.6	1.47675E-05
5	50079	79.06	100	1.5787E-05	47670	78.15	97	1.59021E-05
6	57268	94.04	95.32	1.56526E-05	53782	92.03	93.4	1.59824E-05
7	49932	79.71	87.64	1.39905E-05	46136	81.08	85	1.49379E-05
8	65934	92.67	91.09	1.28026E-05	61332	91.29	92.5	1.37682E-05

9	52111	78.61	86.97	1.31196E-05	50175	80.54	85.3	1.36923E-05
10	55060	85.51	92.6	1.4381E-05	53516	83.09	94.7	1.47032E-05
11	58675	85.8	90.92	1.32952E-05	55499	84.41	89.1	1.35516E-05
12	57101	90.46	90.76	1.43783E-05	56041	91.73	89.4	1.46333E-05
13	66295	100	90.75	1.36889E-05	60004	100	91.7	1.52823E-05
14	46406	76.81	94.46	1.56349E-05	43097	74.87	96.2	1.67124E-05
15	62098	80.02	83.57	1.07689E-05	61406	78.96	85.4	1.09813E-05
16	63000	92.69	83.35	1.22631E-05	58130	91.2	85	1.33357E-05
17	58867	79.44	84.84	1.1449E-05	54237	80.97	86.6	1.29285E-05
18	58375	79.53	84.04	1.14496E-05	55686	78.66	82.5	1.16537E-05
19	58362	80.42	76.87	1.05923E-05	56367	78.97	77.9	1.09137E-05
20	59424	72.44	90.4	1.10201E-05	54519	70.39	88.8	1.1465E-05
21	59261	79.82	87.44	1.17775E-05	54888	81.68	89.6	1.33336E-05
22	57040	64.47	88.78	1.00344E-05	55712	65.21	87	1.01832E-05
23	51978	61.69	72.5	8.60459E-06	48251	59.93	70.4	8.74403E-06
24	57037	77.66	83.36	1.135E-05	54696	76.35	85	1.1865E-05
25	61235	84.01	82.44	1.13102E-05	56401	82.07	81.1	1.18011E-05
26	62403	74.4	93.49	1.11464E-05	60632	73.14	95.4	1.15081E-05
27	60197	74.82	83.9	1.0428E-05	54914	73.38	86.2	1.15186E-05
28	62659	90.57	93.55	1.35222E-05	59637	89.17	90.9	1.35914E-05
29	50402	65.04	80.58	1.03981E-05	46210	64.23	81.8	1.13699E-05
30	59537	93.83	88.17	1.38955E-05	55870	91.4	89.3	1.46089E-05
31	61098	80.53	90.97	1.19902E-05	55181	78.99	92	1.31696E-05
32	51515	74.4	72.62	1.0488E-05	49060	72.97	70	1.04116E-05
33	69547	85.24	95.51	1.17061E-05	67041	83.78	93.3	1.16596E-05
34	58964	80.88	82.51	1.13178E-05	54849	78.65	80.6	1.15575E-05
35	59372	75.72	84.23	1.07422E-05	56124	74.07	85.4	1.12707E-05
36	53222	64.93	88.73	1.08249E-05	50648	66.8	90.2	1.18966E-05

37	60685	77.29	86.26	1.09863E-05	59197	75.28	87.7	1.11527E-05
38	64481	87.68	84.33	1.1467E-05	60436	86.61	82	1.17512E-05
39	60258	82.26	81.42	1.1115E-05	56206	80.59	79.9	1.14563E-05
40	64241	87.72	87.91	1.20039E-05	60476	86.28	90.3	1.28829E-05
41	59367	85.92	88.93	1.28707E-05	54759	84.84	90.1	1.39595E-05
42	65367	82.25	85.95	1.08149E-05	59983	79.96	83	1.10642E-05
43	55902	78.54	89.97	1.26404E-05	54433	79.66	88.9	1.301E-05
44	58574	76.41	82.28	1.07335E-05	55930	75.07	81	1.08719E-05
45	62427	93.97	93.49	1.40729E-05	59287	95.15	91.9	1.4749E-05
46	58788	76.29	71.51	9.27991E-06	54159	78.36	69.6	1.007E-05
47	60420	75.39	85.49	1.06672E-05	55702	77.23	87.2	1.20901E-05
48	63484	88.64	80.94	1.13012E-05	60087	90.54	81.7	1.23107E-05
49	63989	98.96	90.59	1.40099E-05	58891	96.3	92.1	1.50604E-05
50	56546	81.32	84.67	1.21766E-05	54361	82.83	86.4	1.31649E-05
51	55355	76.49	90.21	1.24653E-05	53491	74.85	89	1.24539E-05
52	52195	71.93	74.09	1.02104E-05	47810	72.79	75.3	1.14643E-05
53	64494	98.46	93.91	1.43369E-05	60181	95.56	92.5	1.46878E-05
54	58142	71.95	86.3	1.06795E-05	54178	73.82	84.4	1.15E-05

4-2 Comparison of average resilience metrics between the two supply chains in different scenarios

Table 4-11 Average Resilience Results across different consumer zone networks

	Short Supply Network				**Long Supply Network**			
Supply Network Configuration	**Total Cost**	**Availability**	**Connectivity**	**Resilience**	**Total Cost**	**Availability**	**Connectivity**	**Resilience**
2 Consumers	49149	80.94	86.06	1.4225E-05	50118	80.88	86.12	1.42624E-05
3 Consumers	50163	80.96	86.60	1.61673E-05	50288	80.97	82.13	1.61891E-05

5 Consumers	51091	80.96	86.04	1.36837E-05	51045	81.05	85.99	1.37027E-05
10 Consumers	52098	80.10	79.35	1.34954E-05	53027	81.41	86.47	1.30973E-05
15 Consumers	53886	79.36	81.23	1.33367E-05	54038	81.79	86.34	1.31538E-05
20 Consumers	55011	79.90	82.27	1.29193E-05	59998	81.69	86.41	1.31408E-05
25 Consumers	58434	81.60	84.90	1.21961E-05	60980	83.00	88.65	1.28338E-05

We did not calculate the connectivity and availability (hence the resilience) for the base scenarios as this would be the redundant (both are 100% in the base scenario).

When comparing networks that consist of 2, 3 and 5 consumer zones, the short supply chain achieves marginally better performance in terms of cost efficiency and system resilience. The short supply chain costs $49,149 at 2 consumer zones which is slightly cheaper than the long chain's $50,118 and achieves a resilience score of 1.4225E-05 which is slightly lower than the long chain's 1.42624E-05. At 3 consumer zones the short supply chain remains less expensive at $50,163 in comparison to $50,288 for the long chain while achieving resilience scores of 1.61673E-05 and 1.61891E-05 respectively. The short chain's cost reaches $51,091 at 5 consumer zones which is marginally higher than the long chain's $51,045 though its resilience score of 1.36837E-05 stays competitive against the long chain's 1.37027E-05.

These smaller supply chain setups allow the short chain to operate with shorter transportation routes and minimal intermediary involvement. The short chain displays better connectivity at 3 consumer zones (86.60% vs. 82.13%) which enhances its capability to preserve operational subnetworks after disruptions which is essential for resilience measured by RLS = 1/TC * Con (%) * Avl (%). Both supply chains demonstrate similar availability figures (80.96% vs. 81.05% at 5 zones) which shows competencies in serving consumer zones for small-scale operations though the cost benefits of the short chain decrease with increased scale.

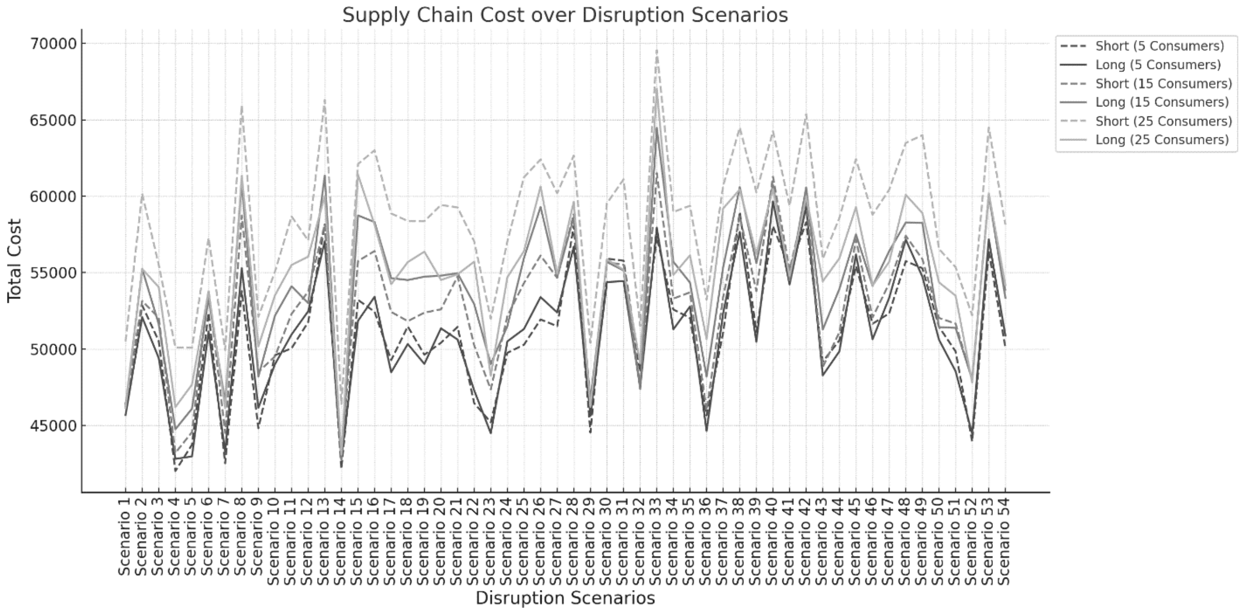
Larger network sizes of 10 consumer zones lead to conventional supply chains developing resilience advantages. At 10 consumer zones the short chain costs $52,098 and has a resilience level of 1.34954E-05 but the long chain that costs $53,027 achieves lower resilience at 1.30973E-05. The superior availability (81.41% vs. 80.10%) and connectivity (86.47% vs. 79.35%) of the long chain outweigh its higher operational costs. The long chain keeps network stability during disruptions because its diversified sources and redundancy help protect against the localized vulnerabilities of the short chain.

The pattern becomes stronger when consumer zones reach 15, 20 and 25 points. At 20 consumer zones the short chain costs $55,011 and achieves resilience of 1.29193E-05 compared to the long chain which costs $59,998 but achieves higher resilience at 1.31408E-05 through improved availability (81.69% vs 79.90%) and connectivity (86.41% vs 82.27%). Although the cost gap expands to $58,434 versus $60,980 by 25 consumer zones, the long chain shows better resilience of 1.28338E-05 compared to the short chain's 1.21961E-05 because it reaches peak connectivity levels of 88.65% and availability rates of 83.00%. The trial results indicate short chains become vulnerable to cost spikes and connectivity losses when applied to larger communities while long chains use structural robustness to handle disruptions effectively.

4-3 Total Cost comparison between the two supply chains in different scenarios

In terms of total costs, short supply chains tend to be cost-effective for 2–5 consumer zones, reflecting simpler routes, fewer intermediaries, and minimal overhead. Yet, in scenarios with 15–25 consumers, the tables show the total costs for short networks climbing above those of the long chains in a sizable portion of disruptions. In particular, if a local production hub is heavily disrupted, the cost of rerouting or scaling up replacement supply can spike more dramatically for short than for long. By contrast, the conventional, long-distance supply chain benefits from diversified sourcing at higher network sizes, which often yields lower overall costs except in disruptions that sever a major international route—though those "choke-point" events do appear in some scenarios, causing cost spikes for the long chain as well.

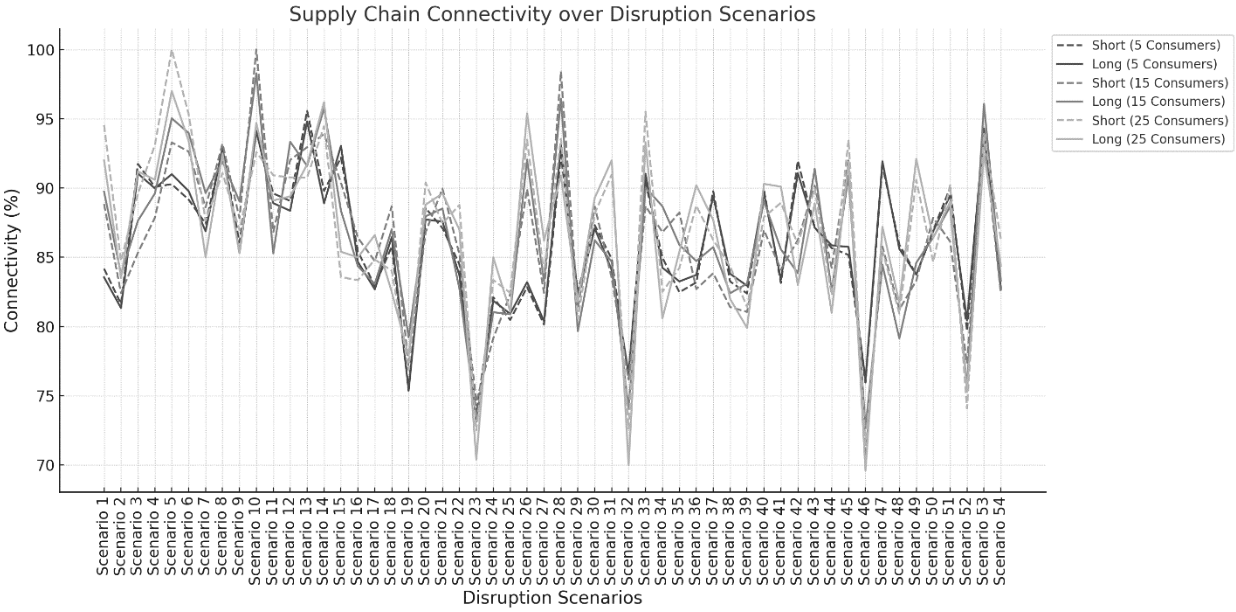
These results are depicted below using supply networks with 5, 15, and 25 consumers as representatives for small, medium, and large networks respectively. The other networks are not included in the plots below for the sake of higher visibility.



4-1 Cost Comparison between the two supply chains in different scenarios.

4-4 Connectivity comparison between the two supply chains in different scenarios

Secondly, the connectivity parameter (ratio of the largest functional subnetwork to the overall network) showcases the following behaviours. For small short networks, connectivity rarely collapses below 75%, because losing one arc does not always isolate more than one or two consumer zones. Yet for 15- or 20-consumer short networks, losing one critical node or corridor can reduce connectivity more severely, as many downstream consumers become cut off. The long chain can appear more robust in partial disruptions—maintaining a large connected subcomponent—but might show abrupt connectivity losses when a key international port or rail link is disrupted, slicing off entire regions at once.



4-2 Connectivity Comparison

4-5 Availability comparison between the two supply chains in different scenarios

Turning to availability (i.e., the fraction of consumer zones still served), the tables show short networks generally achieving high availability in mild or regionally targeted disruptions; local nodes can often redirect supplies fairly quickly if a single route fails. However, in several broader or repeated disruptions—especially scenarios that take out major local processing capacity—the short chain's availability can dip below 80% (or even 70% in worst-case rows), reflecting its vulnerability to a single point of failure. Meanwhile, the long chain sees fewer extreme availability drops under smaller shocks, but it can plummet when cross-border or multi-province routes are lost, indicating that a global chain is more susceptible to large-scale logistic or border issues.

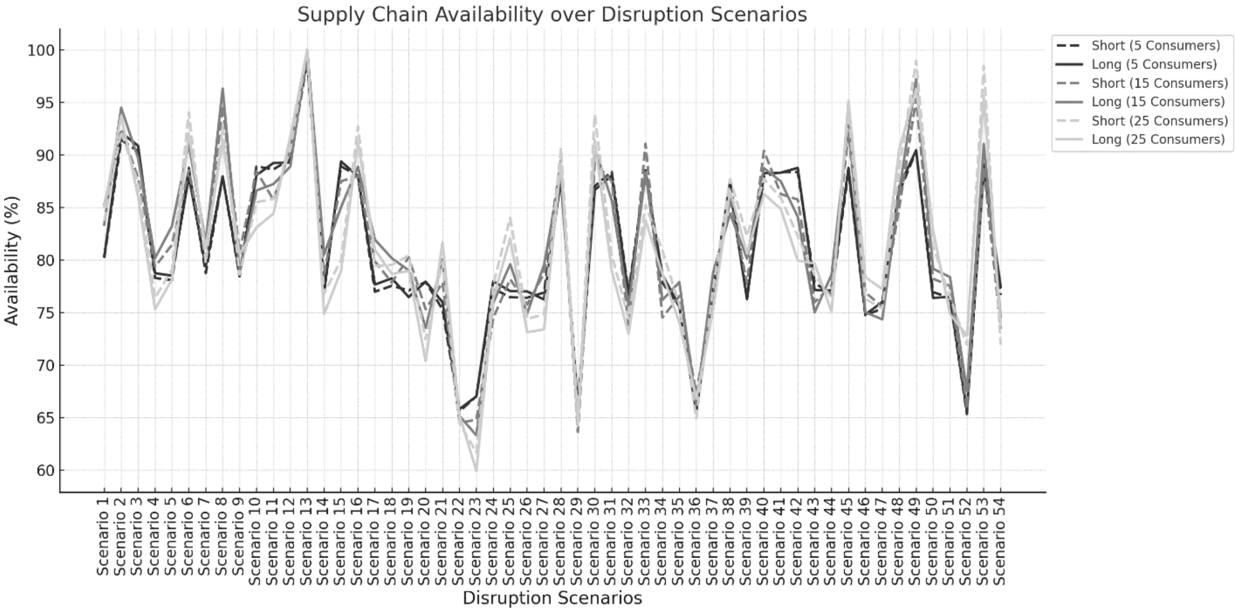


Figure: 4-3 Availability Comparison

4-6 Resilience comparison between the two supply chains in different scenarios

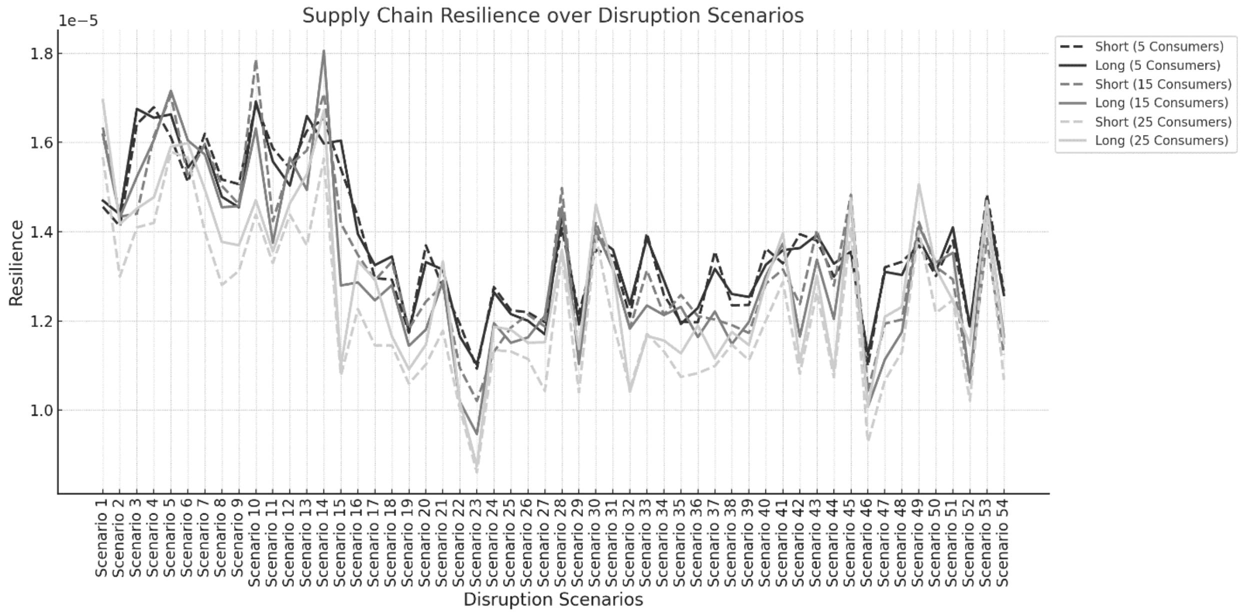


Figure: 4-4 Resilience results

Across the disruption scenarios, the resilience metric (RLS=1Cost×Connectivity×Availability) consistently underscores a trade-off between financial and network-structure factors. For smaller networks (2–5 consumer zones), short supply chains typically exhibit slightly higher resilience: they maintain moderate costs while sustaining strong connectivity and availability when localized disruptions occur. However, once the network scales to 10 or more consumer zones, the long chain's resilience scores often come close or even surpass those of the short chain, driven primarily by larger absolute costs on the short side and, at times, dips in connectivity when a single local node fails. That pattern suggests that local, short-range networks thrive for small communities but may need extra infrastructural investment to uphold high resilience at larger scales.

4-7 Correlation analysis among connectivity, availability, and cost

Network expansion leads to improved supply chain availability and connectivity which demonstrates the network's increased redundancy.

The statistical correlation analysis between connectivity and availability shows a moderate positive correlation with a coefficient value of 0.461. The data indicates a pattern where higher connectivity levels result in better availability outcomes. The observation stands true provided that consumer areas maintain their links to supply sources which keeps their food access stable. The correlation does not reach perfection since its value is below 1 because other elements like disruption severity and location affect availability.

The decline in connectivity from disruptions leads to reduced availability and threatens food access especially in geographically vulnerable regions while negatively affecting food security. Supply chains require further risk mitigation strategies beyond redundancy because major disruptions that cause both connectivity and availability to drop need protection through measures like alternative routing and backup storage capacity.

The correlation analysis demonstrates that availability has a strong positive relationship with total cost as shown by a coefficient value of 0.741. The link between higher costs and better availability likely exists because expensive networks have the financial ability to invest in multiple routes, maintain larger inventory buffers and use various transportation methods to ensure continuous food supply during disruptions. Investing in redundant systems and multiple distribution channels improves supply chain resilience because consumer zones receive consistent supply even during disruptions.

The analysis shows that resilience and connectivity maintain a strong positive correlation with values ranging from 0.78 to 0.79 across most scenarios. Higher levels of connectivity result in improved resilience. Connectivity indicates the supply chain's ability to maintain functionality during disruptive events. A supply chain that utilizes several routes and redundant connections can continue functioning when certain paths become obstructed. Short supply chains demonstrate the highest correlation to resilience because disruptions impact fewer nodes in these systems. Direct enhancement of resilience occurs when connectivity improves through the addition of alternative routes and backup suppliers or storage hubs.

The link between resilience and availability shows moderate to strong positive correlation values between 0.56 and 0.60. When food supply remains available during disruptions the supply chain shows greater resilience. The practice of maintaining steady product availability through stockpiling methods alongside better logistics and local manufacturing results in stronger resilience.

The correlation between resilience and total cost remains weak and close to zero with values mostly between -0.05 and -0.08. Reduced expenses lead to enhanced resilience performance. The network becomes more fragile with cost-saving measures like local sourcing because expensive logistics operations such as long-distance shipping build resilience.

Smaller networks consisting of 2 to 5 consumer zones demonstrate stronger correlations between their resilience and connectivity or availability. The correlation between supply chain attributes and performance metrics becomes less pronounced when the network expands to cover 10-25 consumer zones. Disruptions affect smaller networks more significantly while larger networks maintain stability through increased redundancy.

Chapter 5 Conclusion

This research set out to quantitatively compare the resilience and performance of short (localized) versus conventional (long-distance) supply chain networks in the context of alleviating food insecurity—using raspberry production as a case study. By employing a hybrid simulation-optimization approach over 54 distinct disruption scenarios, we integrated key performance metrics—total cost, connectivity, and availability—into a single resilience index (RLS). Our framework, built upon both deterministic cost/inventory/transportation parameters and disruption-induced variations, enabled us to capture the complex trade-offs inherent in supply chain design.

In regards with resilience and cost trade-offs, in small-scale networks (2–5 consumer zones), short supply chains tend to be more cost-effective. Their reduced transportation distances, fewer intermediaries, and lower overhead translate into lower total costs and, in many cases, higher resilience scores. For larger networks (10–25 consumer zones), however, the cost advantages of short supply chains diminish. Localized networks can suffer dramatic cost spikes when a single node or corridor is disrupted, resulting in lower connectivity and availability. In contrast, conventional (long-distance) supply chains often benefit from diversified sourcing and built-in redundancies that maintain network integrity even when key links are affected.

Moving to network Structure and redundancy, our analysis revealed a strong positive correlation between connectivity and resilience, suggesting that supply chains with multiple, redundant routes better absorb shocks. Availability—the fraction of consumer zones still served—also improved with increased connectivity. However, the correlation between cost and resilience was weak, indicating that while cost efficiency is important, it does not automatically ensure a resilient network.

Additionally, implications of scale showcase themselves as short supply chains appear best suited for small, localized regions, such as the Northwestern Territories of Canada, where the benefits of reduced transportation distances are most pronounced. As network complexity increases, conventional supply chains—with their diversified sourcing and multiple logistic channels—tend to better maintain overall connectivity and availability, even if at a higher operational cost.

5-1 Contributions and Managerial Implications

The research presents multiple contributions to the study of supply chain resilience.

• Quantitative Framework: Our research introduced a hybrid simulation-optimization model which merges cost factors with connectivity and availability measurements into one comprehensive resilience metric. The framework presented in this study shows adaptability to different agricultural commodities and various geographical areas.

• Empirical Insights: The results of our research dispute the traditional belief that extended supply chains provide superior cost efficiency because our study proves that regional supply networks with shorter distances achieve better resilience during specific disruptive events. Supply chains with only two to five consumption zones benefit from both improved resilience and cost performance when they maintain shorter supply chain lengths.

• Strategic Guidance: Supply chain managers and policymakers should prioritize both efficiency and robustness according to our research findings. Regions with poor transportation systems can improve food security through local production investments because these investments lower both cost and vulnerability.

Policymakers working in food security and supply chain sustainability will find the research findings especially applicable. National food systems become more resilient when supply networks diversify and adopt advanced technologies. Supply chain and agricultural sector policymakers and practitioners must pay attention to the necessity of establishing systems that can withstand disruptions. The research shows that investing in local supply chain facilities can boost system resilience. Providing incentives represents an essential measure to support both the establishment and maintenance of local farms and production plants. The available incentives consist of tax breaks and government funding in addition to low interest loans and infrastructure development. Investments in remote area food supply chains lower costs while creating employment opportunities and minimizing carbon emissions which aligns with sustainable development principles.

This research provides supply chain management professionals working in agriculture with information about the relationship between efficiency and resilience. The research promotes comprehensive supply chain design strategies which extend past traditional constraints of distance and localisation. Applying this research to varied agricultural products across different regions will enable supply network optimization that matches specific disruption patterns while identifying potential bottlenecks and preparing for future disruptions.

5-2 Policy and Future Research Directions

This study identifies multiple areas for future research and policy measures because supply chain disruptions have become more frequent due to pandemics, climate-related events and tariffs.

- Broader Applicability: Researchers should extend our resilience model to other products and regions while including past disruption data to improve and confirm its effectiveness.

- Technological Integration: Future research should explore how digital supply chain tools like IoT and real-time monitoring systems can improve connection capabilities and speed up recovery processes after disruptions.

- Environmental and Socio-Economic Impact: Research needs to investigate how supply chain configuration choices affect carbon emissions, local employment opportunities, and community health.

- Decentralized Strategies: When supply network systems expand in size they should explore decentralized storage options and alternative routing techniques alongside multiple sourcing methods to protect supply chains from all types of vulnerabilities.

5-3 Final Remarks

Food security needs new supply chain approaches because current systems cannot handle today's extraordinary uncertainty. Our research indicates that resilience requires more than cost efficiency to maintain connectivity and availability during disruptions and remains essential for sustainable long-term operations. Small communities can benefit from short supply chains as their optimal solution while larger networks should integrate localized systems with conventional ones to achieve optimal performance. This study delivers a strong analytical foundation enabling stakeholders to develop supply chain systems which maximize efficiency while remaining durable against global volatility disruptions.

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