Building Resilient Supply Chain using Interactive Visualization

by

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Submitted to the
Department of Engineering and Management
In Partial Fulfillment of The Requirements for the Degree of

Master of Science in Engineering & Management

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ABSTRACT

As supply chains expand globally and companies pursue speed, efficiency, and reduction in cost, the probability of disruptions propagating through the network grows. There are many documented threats to global supply chains: political instability, natural disasters, dock strikes, poor product quality, communications failures, currency risks, cyber-attacks, and recently a pandemic. These disruptions often incur additional costs and require time to respond and recover from these disruptions. Companies realize the importance of resilience in the supply chain network. However, due to the complex nature of the network, traditional processes, and outdated technology, the leadership team cannot make proper decisions against such disruptions. On the other hand, we found evidence of the importance of interactive visualization in decision-making. This research project introduces the application of interactive visualization in supply chain resilience decision-making. The application can be broken down into three parts. Firstly, a backend mixed-integer linear programming model that solves for a minimum total cost based on the inputs. Secondly, a front-end UI allows users to create any disruption scenarios using parameters - geography, time period, product, to visualize disruption such as demand variation, a shutdown of transshipment location, or a change in transportation mode. Lastly, a JSON file that connects the front and back end seamlessly. We use the application to create scenarios that are relevant for a multinational company. For the first use case, we explore the consequences of a shutdown of airports near distribution centers. For the second use case, we explore the availability of more than one transportation mode per lane. We analyze the results from the use cases to plan mitigation strategies for any such disruptions in the future. In conclusion, by creating scenarios and visualizing the network in a single and easy-to-understand application, we facilitate decision-making to test the network's resilience.

Thesis Advisor: Dr. Matthias Winkenbach
Title: Director MIT Megacity Logistics Lab, Director MIT CAVE Lab

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CHAPTER 1: INTRODUCTION

1.1 Nature of Modern Supply Chain Network

The last several years have seen an increasing frequency of supply chain disruptions (Burnson, 2019). Furthermore, the damages to the shareholders from these disruptions have been growing. Suppliers are unable to supply. Ports are closed. Transportation links are down. Regardless of the cause of a disruption—pandemic, hurricanes, floods, political actions, or economic downturn—such external events are growing in magnitude and frequency, making the supply chain more brittle and vulnerable (Hendricks and Singhal, 2003). Additionally, the nature of the supply chain itself is changing in this modern era. Supply chains now operate with little inventory on a just-in-time basis (Vokurka and Lummus, 2000). Globalization plays a role by adding several entities involved and stretching the lead time. The increasing variety of goods leads each of these goods to sell in smaller amounts and thus be more prone to demand uncertainty. Also, the short life cycle of goods means that there is little history to go on. Finally, increasing customer expectation in terms of availability, delivery time, and pricing makes companies more vulnerable.

1.2 Supply Chain Resilience

1.2.1 Definition

Christopher & Peck (2004), following their research on building resilient supply chain in Cranfield University, defines supply chain resilience as the ability of a system to return to its original state or move to a new and more desirable state after being disturbed. During the same time, following a three-year research project on organizational resilience in MIT, Sheffi (2005) makes an interesting transition to the definition of resilience. He states that supply chain
resilience no longer implies the ability to manage risk but also the opportunity of a supply chain to be better positioned than the competition and even gain an advantage from disruptions.

1.2.2 Covid-19: The Stress Test

The COVID-19 pandemic is the stress test that caught most companies off guard and offered no time to prepare. Organizations have had to deal with rapid spikes and declines in consumer demand, production downtime, and supply and transport delays. The pandemic highlights the impact of such volatility on supply chain risk. It exposes the underlying complexities and vulnerabilities of the global supply chain network and illustrates the importance of resilience in the supply chain.

The COVID-19 has raised serious questions on the resilience of the global supply chains network. According to Mckinsey (2020), a vast majority of the organizations (93%) mentioned that post-COVID, their key priority is to increase supply chain resilience. Furthermore, 44% also said they plan to increase investment in building supply chain resilience.

Similarly, Capgemini (2020) reports that the crisis has impacted more than 80% of organizations, and many are struggling with significant challenges across all aspects of their operations. They include shortage of critical parts (74%), delay in shipments and longer lead times (74%), difficulties in adjusting supply in response to fluctuating demand (69%), and difficulties in planning amidst high levels of volatility in customer demand (68%). Capgemini’s research included organizations from all the sectors – retail, consumer products, discrete manufacturing, and life sciences – and all report similar challenges across their supply chains.

1.2.3 Decision Making for Supply Chain Resilience

Even though companies know the importance of a resilient supply chain, it is easier said than done to implement supply chain resilience. Schrage (2020) mentions that during the COVID
pandemic, “the top management literally could not see what was happening — or needed to happen — to ensure safe and reliable deliveries under duress."

According to Deloitte (2014), 71% of the executives consider supply chain risk as an important part of their decision-making. Nevertheless, only 30%-40% of them have effectively implemented data visualization or analytics to deal with supply chain risk management. This disparity shows that even though companies realize the importance of a resilient supply chain, they lack the tools to make better strategic decisions to achieve resilience.

1.3 Outline

We propose a supply chain visualization application to evaluate resilience in the network. The purpose of the application is to model and visualize the organization’s supply chain network to run "what-if" scenarios. The three key elements of the application are: (1) Visualize the entire supply chain network, (2) Create disruption scenarios to plan for supply chain risk mitigation strategies, (3) Analyze results to develop rapid responses to unplanned events. The supply chain is analyzed under different conditions and risk assumptions through the optimization model running at the back end. By doing so, the vulnerability of the existing supply chain network is evaluated based on data.
CHAPTER 2: LITERATURE REVIEW

The previous chapter highlights the importance of resilience for a global supply chain network. It also discusses how the supply chain industry needs to embrace technological advancements to manage risks while keeping a lean network. In this chapter, we will review the research work that has been carried out for the resilient supply chain network and visualization of the supply chain network. Section 2.1 discusses why a resilient supply chain is important. Section 2.2 introduces the frameworks and methodologies used to build a resilient supply chain. Section 2.3 highlights the importance of visualization of a supply chain network. Section 2.4 discusses the research approach for the thesis.

2.1 Need for Resilient Supply Chain

Like any other aspect of an organization in a business, supply chain networks face risks while operating in this world due to uncertainties. For the network to operate and grow with all kinds of uncertainties that arise due to new geographies, products, strategies, it needs to build resilience in the system (Sheffi, 2015).

Due to globalization, supply chains are closely integrated into all countries and economies through clusters of networks. This has a significant impact on society as it improved world trade, foreign investment, and technology flow, among other things. However, it is essential to recognize how critically important these networks are, as even a complication with a single entity from the network can result in cascading disruptions that can bring down the supply chain and all the economies associated with it (Anbumozhi et al., 2020).

In this new era, supply chains are not ‘linear’ structures anymore. Instead, it is a tree with a multitude of branches and a complex root system, with the trunk of the tree representing the processes of the focal firm. Hence, it is essential that businesses and those who manage them
understand the full extent of the network they are a part of and systematically explore the network to identify its vulnerabilities (Christopher and Peck, 2004a).

Lastly, investing in a resilient supply chain should not be scoped only under risk management. Unlike insurance, it can improve overall revenues and reduce operating costs. A company with a resilient supply chain network can take strategic risks to generate growth, thereby decreasing the likelihood of becoming irrelevant in this dynamic global economy (Sheffi, 2015).

2.2 Build Supply Chain Resilience

The first step to building a resilient supply chain is to understand its importance and the frameworks to leverage by the leadership.

Many researchers have developed frameworks to build/test the resiliency of a supply chain network. Christopher and Peck (2004b) have developed a framework for a resilient supply chain. Their four principles include: (1) resilience can be built well ahead of disruption by re-designing, (2) identifying and managing risks requires strong collaboration, (3) being agile is essential to deal with unforeseen events in a swift manner, (4) business need to build a culture of risk management.

Sheffi (2007) proposed a general framework to invest in building a resilient network. It includes detection, prevention, and response. Addressing the items in each stage of this framework reduces the duration, probability, and effects of disruption on a network. This framework is supported by a process that classifies risks on a 3-dimensional axis of probability, consequence, and detectability (lag) to evaluate the impact of the particular disruption. In general, Yossi mainly advocates for three items to build resiliency: (i) increasing redundancy by having many supplier options and have extra inventory, (ii) building flexibility by having concurrent and
standardized processes, (iii) changing the culture by having constant open communication and having distributed power to take necessary actions.

Similarly, Sáenz and Revilla (2014), based on their research understanding of Cisco's supply chain disruption due to hurricane Katrina, define an approach to building a resilient supply chain network: (a) business identifies its priorities for a long term, (b) map all the vulnerabilities of the network for visibility, (c) risk awareness is integrated to the team, product and value chain, (d) monitor resiliency by identifying the right metrics, (e) keep an eye out for disruptive events.

All the frameworks have multiple common aspects of building a resilient supply chain network, such as (1) understanding the network, (2) building flexibility and redundancy, and (3) building a culture of risk management.

2.2.1 Test Resiliency of the Supply Chain Network

According to some researchers such as Simchi-Levi (2020), an effective way to evaluate the resiliency of a supply chain is by mapping the network – suppliers, manufacturing plants, distributors, and applying a stress test to check for disruptions. This will allow businesses to identify bottlenecks or hidden risks in various unexpected places and act quickly to fix the weak links in the network.

This is reiterated by Le Merle (2011), according to him, a disrupter stress test needs to include the four steps: (1) mapping the entire supply chain network, (2) creating a list of potential disrupting items, (3) exploring "what-if" scenarios for each of them, and (4) implementing a back-up plan for such cases.

2.2.2 Supply Chain Decision Making

Over the years, organizations have focused on making their supply chains more efficient. However, whenever disruptions hit for an extended period, like the COVID-19 pandemic,
supply chain that is not equipped or flexible enough can break or, at a minimum, burden the organization. Consequently, managing and controlling risk is a crucial piece of effective supply chain management (Black and Segura, 2020).

Flynn, Schroeder & Sakakibara (1995) state that creating and implementing a risk management framework will require collaboration among the whole supply chain structure. Without leadership backing, developing a pandemic risk management framework will have low chances of attainment. Therefore, leadership is a significant success factor in world-class management. March & Shapira (1987) have found that when managers underestimate the degree of severity of a supply chain risk, it is because they do not have the required data to estimate the potential cost/benefit of such disruption. Ivanov and Dolgui (2020) have found that more complex networks are more susceptible to severe disruptions. Thus, having better visibility and communication in the end-to-end supply chain can help decrease the effects caused by uncertainty.

Schrage (2020) has found that currently, supply chain operations are heavily reliant on Spreadsheets and ERPs. Therefore, when faced with disruption, lack of visibility in the supply chain has made it difficult for senior leadership to truly understand the changes in the supply chain network. As a result, organizations have learned the importance of supply chain digitization with a focus on providing visibility to leadership, so they assess to take decisions.

2.3 Importance of Supply Chain Visualization

Visualization can be a very useful tool for risk evaluation. According to Gardner and Cooper (2003), people find it easier to process visual information than textual information. Research shows that supply chain managers can easily understand the network when overlaid with a map.
Unlike other maps, the supply chain map is focused on the big picture rather than details. It includes necessary items such as locations, products, and connections.

2.3.1 Visualization in Decision Making

Supply chain visualization goes beyond just bringing visibility to the network. It is also used for decision-making by senior management. A visualization tool gives a clear overview of the entire operations and highlights patterns and bottlenecks (Goh et al., 2013). Visualization goes beyond just data network visibility, as it includes ease of transfer and exchange of knowledge across the management. It enables linking the strategic plan and evaluating risks in the network (Gardner and Cooper, 2003).

Senior management’s ability to react to rapidly changing supply chain conditions has a high impact. Visualization of large and scattered data provides the proper context to the senior managers to enable them to make the best decision in a fast and effective way (Lou et al., 2020).

2.3.2 Interactive Visualization

One of the important categories in the visualization of decision-making is interactive visualization (Singh et al., 2019). Visualization alone does not allow for successful analysis; it requires effective interaction techniques. Such interactions allow users to explore, engage and make sense of the underlying data, thus enabling a better reasoning process. The process essentially has three steps: view data specification, view and manipulate data, and analyze the results (Heer et al., 2012).

Visualization fused with interaction is an emerging field in organization science. It allows decision-makers to effectively comprehend data, visualize patterns and trends, and identify risks, thereby facilitating hypothesis generation and evaluation and improving decision making (Basole et al., 2017).
2.3.3 Supply Chain Network Design

Supply Chain Networks (SCNs) are composed of nodes and arcs. The nodes can be (1) external suppliers, (2) production centers, (3) distribution centers (DCs), and (4) demand zones. Similarly, arcs illustrate the different transportation lanes that could be used to move materials (See Figure 1). In order to create a robust SCN, possible alternative scenarios must be analyzed to design a robust value-creating network. Besides including regular changes in demand, variable costs, material prices, and exchange rates, business operations interruptions should also be considered (Klibi and Martel, 2012).

![Supply Chain Network Structure](image)

*Figure 1. Supply Chain Network Structure Retrieved from Klibi and Martel (2012).*

To design a supply chain network, determine plants' optimal location and capacity, distribution centers (DCs). The most straightforward network design problem is deciding where to build DCs that serve as stocking and shipping points between existing supply plants and retailers. This is formulated as a mixed-integer linear program (MILP). Data requirements include annual aggregate demands for the product at each retailer, supply capacities, unit shipping costs between the shipment locations, and the annual fixed cost of operating a DC at each potential location. Decision variables include the quantity to ship between locations and binary variables that
indicate if each DC should be open or closed. The objective function minimizes total shipping and fixed DC costs. Constraints ensure that demand is met at all locations, that companies only ship products from a DC if it is open, and that all plant capacities are respected. The solution provides the location (i.e., where to open the DCs) and the allocation of plants to the DCs, the allocation of DCs to retailers, and the capacity of each DC (Souza, 2014).

2.4 Research Approach

We know the importance and the need for a resilient supply chain network in the modern era from the literature review. We have learned the most commonly used frameworks to build a resilient supply chain network and stress test an existing supply chain network. We have also learned that even though the senior management realizes the importance of resilience, they cannot take optimal decisions on time because they do not have the necessary data available. Additionally, we have studied the importance of visualization in the supply chain, especially regarding decision-making and how interactive visualization can enhance decision-making.

The literature review shows there is room for improvement in decision-making for a resilient supply chain network. The research aims to build an interactive visualization platform to create potential disruption scenarios and visualize the result. It will allow the organizations to test the network's resiliency with less effort and hence make accurate decisions in less lead time.
CHAPTER 3: METHODOLOGY

In this section we define the methodology and the required steps to conduct this research.

This section can be broken down into four actions: (1) Data collection; (2) Data Cleaning and preparation; (3) Problem formulation, and (4) Model Interaction.

3.1 Data Collection

In this step we gather data from a multinational manufacturer regarding (1) Historical Delivery Data, (2) Cost/Rate Sheets, and (3) Forecasting Data.

Historical Delivery Data

The historical data is classified in the following categories (a) Shipments, (b) Nodes, (c) Products, and (d) Costs. The shipment details should include the pick-up and delivery dates, shipment IDs, transportation mode, the gross weight and volume of the shipment. The Node details should include the type of nodes such as origin, destination or transshipment. It also needs to include the city, and country of origin and destination. The product details should include the product name or ID, weight and volume. This data will allow us to setup the initial network required to build and visualize the model.
Cost/Rate Sheets

The rate sheets should include all the cost data associated with each lane. This is because the cost for each lane varies based on volume and the type of transportation mode. A rate sheet with a detailed cost data allows us to calculate accurate costs for each scenario run by the model.

Forecasting Data

The forecast model is categorized in three categories (a) Locations, (b) Product and (c) Timeline. The location data should include the demand city and country. The Product details should include the product ID or name and forecast demand volume/units. Lastly the timeline should indicate time frame of the demand. The forecasting data allows us to build base demand scenarios. The users can then build demand variation use cases.

3.2 Data Preparation

In this section we discuss how we prepared the data after collection. We cleaned the historical, forecast data and also the rate sheets by removing the data with missing columns or irrelevant observations. We fixed the structural errors across all the historical and product data – such as different version of the same name. We filtered out unwanted outliers – such as improper data entry, or irrelevant data columns. We handled missing data – Any empty cell data will prevent from the algorithm to run smoothly, hence the missing numeric data was changed to 0, and character data were named as “Not Applicable”. Lastly, we validated the data with the data providers before proceeding further.

For the next step, we identified the location of the individual nodes. We need to represent all nodes (origin, destinations and transshipment locations) on a world map. Hence, we got their geographic coordinates i.e., latitude and longitude for all locations using the geopy API. For the addresses that we could not get the coordinates using the API, we used google maps.
For the next steps, we need to ensure that datasets can be mapped to each other. All the data we received was segregated, yet we need to connect the data sets together to build the system. We identified and made sure that the data list used to map datasets had common data attributes. We ensured that there were costs associated to each lane. We also reviewed that the range of costs was according to the transportation modes and the volume of the shipment. Lastly, we aggregated the daily historical data over monthly period to get monthly historical demand. This was used to do the initial analysis of data to form use cases and run them.

3.3 Problem Formulation

The mathematical model in this project tries to minimize the cost of transportation, while fulfilling the demand to all the customers that need to be served by destination.

Table 1: Sets and indices

<table>
<thead>
<tr>
<th>P</th>
<th>{0, 1, …, p}: Set of product types in the network</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>{0, 1, …, s}: Set of shipment types</td>
</tr>
<tr>
<td>T</td>
<td>{0, 1, …, t}: Set of time periods (months)</td>
</tr>
<tr>
<td>I</td>
<td>{0, 1, …, i}: Set of origin nodes</td>
</tr>
<tr>
<td>J</td>
<td>{0, 1, …, j}: Set of destination nodes</td>
</tr>
<tr>
<td>D</td>
<td>{0, 1, …, d}: Set of final order destinations</td>
</tr>
</tbody>
</table>

Table 2: Decision Variables

<table>
<thead>
<tr>
<th>( f_{ijst} )</th>
<th>Flow of shipments (in number of units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{ijstp} )</td>
<td>Flow of product per shipments (in number of units)</td>
</tr>
</tbody>
</table>
Table 3: *General Parameters*

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{ijst}$</td>
<td>Cost of transportation per unit during month $m$ through shipment type $s$ between origin $i$ and destination $j$</td>
</tr>
<tr>
<td>$q_{dpt}$</td>
<td>Demand for product $p$ during the time period $t$ for destination $d$</td>
</tr>
<tr>
<td>$F^P$</td>
<td>Set of packaging sites</td>
</tr>
<tr>
<td>$F^T$</td>
<td>Set of transshipment points such as port or airports</td>
</tr>
<tr>
<td>$F^A$</td>
<td>Set of distribution centers</td>
</tr>
<tr>
<td>$M$</td>
<td>A very large number</td>
</tr>
</tbody>
</table>

The following formulation of the mathematical optimization model is used for the analysis:

$$MIN \sum_{d \in T} \sum_{i \in I} \sum_{j \in J} \sum_{s \in S} f_{ijst} \ c_{ijst}$$ (1)

Subject to

$$\sum_{i \in F^P} \sum_{s \in S} f_{ijst} \ X_{ijstp} = q_{jpt} \ \forall j \in D, \forall p \in P, \forall t \in T$$ (2)

$$\sum_{i \in F^P} \sum_{s \in S} f_{ijst} = \sum_{k \in F^A} \sum_{s \in S} f_{jkst} \ \forall j \in F^T, \forall t \in T$$ (3)

$$\sum_{i \in F^P \cup F^T} \sum_{s \in S} f_{ijst} = \sum_{k \in F^D} \sum_{s \in S} f_{jkst} \ \forall j \in F^A, \forall t \in T$$ (4)

$$\sum_{j \in F^A} \sum_{s \in S} X_{ijstp} \leq M \ a_{ip} \ \forall i \in F^P, \forall p \in P$$ (5)

Equation (1) is the objective function that considers the cost of the overall solution. It consists of the product of flow of shipments and the associated cost of transportation. Equation (2) ensures that demand of each final order destination is satisfied. Equation (3) guarantees the conservation of flow at the transshipment points. Equation (4) guarantees the conservation of flow at the affiliate warehouses. Finally, Equation (5) ensures that the flow of a certain product can depart only from a packaging site associated to that product, where $a_{pm}$ is a parameter equal to 1 if the packaging site $p \in F^P$ is associated to the product $p \in P$ and 0 otherwise.
3.4 Model Interaction

After discussing the problem formulation in the previous section, in this section we design the system to run the model, visually display the result, allow user to interact with it by setting up use cases.

Overall System Design

The overall system design/architecture required to build the application can be split in the four basic criteria. The figure 3 shows the four stages of the system – data input, data pre-processing, optimization model, and visualize result.

The first stage is defining the user query. A user query in this case is a collection of inputs required to solve the model. A user query can be done in many ways. In this case, we are building a system so the user can query using the UI.

In the second stage, the queried data is converted into parameters that the algorithm can read/interpret. These parameters are then processed along with the stored network data for the next stage. The third stage sets up the optimization model which we discussed in the previous section - define our decision variables, objective, and constraints. We also run the model in this stage to get the solution. Lastly, in the final stage, the results are viewed using an UI.

Figure 3. System Design
Define User Inputs

In this section, we will discuss how to define a user-input/query. This is an important aspect of the model as it allows users to create scenarios where they can then simulate on their network, and visualize the results to build a more resilient supply chain network.

The next step is to understand how a user would interact with a supply chain simulation application. So, we did a focused study with a user group – a supply chain team dealing with a global network. We asked what kind of issues they solve on daily basis, and what kind of questions leadership discusses with them. Lastly, if they would use an application to run supply chain simulations, what would they need to evaluate.

We summarized and analyzed these questions to find a common theme of inputs parameters to determine the inputs required to interact with the model. These parameters are (1) geographical scope, (2) distribution network features, (3) demand scenario, and (4) time period. Figure 4 shows an example of what constitutes a user query.

![Figure 4. Structure of a User Query](image)

The geographical scope of the analysis defines the area of interest for a user. The region can be continent, country or a city. The region is used to focus on either the physical transportation nodes within the region, or to understand the demand/supply in the region.

Distribution network features are used to define any and every aspect of the supply chain network. This includes any kind of transshipment facilities, modes of transportation. Users can
either add/remove transshipment locations or modes of transportation to analyze the cost/lead-time of the supply chain network.

Demand inputs allow users to create the scenarios they are interested in. Users can specify what kind of demand or supply variation they want to simulate to enforce this parameter.

Time-period is defined to scope all the previous parameters within a time frame. Users can select the time frame they are interested in to restrict all the data collected and displayed within that time period.

**Convert User Inputs to Model Input**

The objective of this process is to convert the user inputs into parameters used and understood by the optimization model. As figure 5 shows, the process requires a data pre-processing stage so that user inputs can be transferred to the model.

*Figure 5. Data Pre-Processing Structure*

Figure 6 shows in detail on how the pre-processing stage can be done. It discusses how each attribute of the user input is processed and how it interacts with the network data.

To assist with the pre-processing, we need a database structure to maintain and map all the data required to run and visualize the model. The figure 7 shows the database structure.
Hypothesis

In this section we have stated the assumptions that are required for the system to function. On the network level, we assume the demand forecast is defined at a product level. Every product is associated to a certain origin. Every origin and destination pair is associated with a set of...
potential lanes. For existing lanes, a current rate sheet establishes the cost of transportation on the lane as per the transportation mode. For the new lanes, we approximate the lane cost based on distance and weight. Regarding the user, we assume that users have the capabilities to select new potential facilities in the network.
CHAPTER 4: USE CASES AND RESULTS

Using the MILP model and system design defined in chapter 3, we have built an interactive application. It reads the multinational manufacturer’s data that is available to us. First, we analyze the available data to identify potential disruptions in the global network. Second, we identify use cases to explore these disruptions. Third, we create these use-cases in our application. Last, the model finds the optimal solution, displays result for users to measure the resilience of the supply chain.

4.1 Baseline

The first step in analyzing a supply chain network data is to review its structure. Following the methodology outlined in chapter 3, we have cleaned the input data. Visualizing the supply chain network helps to detect the potential issues with the network thereby identifying the right use cases to build resilience in the system.

4.1.1 Supply Chain Network Structure

Figures 8 and 9 show the primary nodes of supply and demand as per the total weight shipped or received annually. The origin nodes are concentrated in Europe (Switzerland, Germany, Italy, and Spain). The rest of 4.5% comes from South America (Brazil). On the other hand, the demand nodes are spread worldwide – majorly in Europe and the United States and Asia, Middle-East, South America.
Figure 10 shows the global network structure and the most frequently used lanes through the year. It shows the major cities that act as either the origin or the demand points.

Figure 11 highlights that only 2 cites act as central hubs. It is because the two cities (Pratteln and Kaiseraugst) have substantial chargeable weights of supply and demand.
The key takeaways from the visual analysis of the network are most locations act as either an origin or a destination. We can say that the multinational manufacturer is a single-tier network. Given the current structure of the global network, there are few opportunities for reconfiguration without introducing additional tiers of facilities.

4.1.2. Transportation Modes

A critical component of network design is defining the arcs and the transportation mode. Figure 12 shows that the primary mode of transportation is via road with 65% of the total volume. An additional 30% of the volume is transported using air, and the remaining 5% using ocean freight. It is also important to note that most lanes are associated with a single transportation mode.
4.1.3. Product Families

We now analyze the products shipped in the network. There are currently 84 products being shipped across the globe. Figure 13 and 14 show the weight distribution of the products according to weight and cost. The figure depicts that 40% of the product accounts for 95% of the total cost globally. Also, 36% of the product contributes to 1% of the total cost/total weight.
4.1.4. Product Lifecycle

We analyze the shipment delivery according to the product lifecycle. The product lifecycles are defined as (A) Established, (B) Late Lifecycle, (C) Resilient, and (D) Launch. Figure 15 shows that 60% of the products shipped are established products, 20% of the product are in the late lifecycle stage, 18% of the products are resilient products, and 2% of the products are in the launch stage.

Next, we understand the shipments of products in different lifecycles as per timeline. The timeline shows the variation of products as per cost and weight. We see a regular distribution of demand for all product categories across the year, with a few exceptions in Q4. The cost of shipping the resilient product goes high during the final quarter without much increase in the demand. The demand for late lifecycle products goes down in the last quarter.

![Figure 15. Product Weight Distribution (Per Product Family)](image)

![Figure 16. Product Weight and Cost for Categories (Per timeline)](image)
4.2 Use Cases Definition

Based on the current status of the network outlined in the previous section, we find potential network disruptions. The current network has a central distribution. Most of the shipments transferred is through two central hubs in Europe. The two hubs are in close proximity to each other. Hence, any issues with or around the hubs will lead to disruption across the global network. Therefore, we will create scenarios to evaluate potential network disruption around a DC. In the following, we will refer to this as Use Case 1.

The current data shows that the network is overly reliant on a single transportation mode for each lane. It is also underutilizing the sea route, which would reduce the overall operating cost for the network. We will create a scenario to evaluate different options of transportation modes. In the following, we will refer to this as Use Case 2.

For both the use cases we are considering the top 5 products as per cost. The top 5 products constitute 45% of the overall product as per weight and cost. The use-cases are limited to the network data available to us from the multinational manufacturer. For the next steps, we display all the attributes of the network on the user-interface (UI). We then find the optimal solution and analyze the results.

4.3 Use Case 1: Network Uncertainties

Figure 17 shows the network structure for this use case. The origin node (orange box) is in Switzerland, Europe. Next to the origin node is a distribution center (red box) and an airport (blue circle). On the other hand, the demand locations (green diamond) are spread across the United States. The demand locations are mainly in the center of the United States, such as in Memphis, Groveport, Nashville, Lockbourne, and Shreveport, except Reno, which is closer to
the west coast. United states have two distribution centers (red box) that also act as a warehouse (yellow triangle), and a series of airports (blue circle) to facilitate the delivery to the shipments.

Figure 17. Use Case 1 Network Structure

4.3.1. Input information

Figure 18 shows the total units of demand to be met for each month throughout the year. The demand across the year is relatively uniform, with a slight increase in the middle of the year.

Figure 18. Use Case 1: Total Demand per Month (in Units)

Figure 19 shows the demand in units for all the locations for the year. The demand is focused in two locations – Lavergne, Memphis. Then in Lockbourne, Jeffersonville, and Gevenport.
Figure 19. Use Case 1: Annual demand per Location (in Units)

Figure 20 shows the demand in units for each product for the year. The product with the highest demand is product A followed by product C.

Figure 20. Annual Demand per Product (in Units)

4.3.2. Optimal Solution

After outlining all the nodes for the use case, we used the model defined in chapter 3 to find the optimal route to delivery. Then, we visualize the solution on a network map.

Figure 21 shows the optimal route to delivery. The first leg of the network is shipped by road to the airport. The main leg of shipment is the air transportation from the origin airport (Basel airport) to the destination airport (Atlanta airport). The shipments are then moved by road to the Louisville distribution center, delivering in the Hillsboro DC, and continuing to Reno.
Cost Analysis

The total cost to operate this network for a year is ~4.43 million USD. Out of which, 3.46 million USD comes from air freight and the remaining 0.97 million USD from road freight. Figure 22 shows the cost distribution of each type of shipment lane. The highest cost is the air freight with 78%. The second highest cost is road transportation from the airport to DC with 11%, followed by the cost to transport the shipment from the warehouse to the customer (6%). The rest 5% is from road transportation of DC fulfillment and origin node to airport.
Figure 23 shows the cost distribution to ship each type of product. This distribution roughly follows the demand distribution of the product. The shipment cost of product A and product C are nearly the same, even though the demand for A is quite higher than C.

![Cost distribution per Product](image)

**Figure 23. Cost distribution per Product**

4.3.3. Scenario 1: Shutting Down Single Airport (Atlanta Airport)

In the previous section, we have visualized the optimal network. We have analyzed that airfreight is responsible for most of the cost to operate this network. Given that the air transportation costs the highest, we run a scenario to disrupt the shipment of goods by air. In this scenario, we shut down the Atlanta airport; the airport used by the optimal solution to deliver shipments. We do not disturb the rest of the network, including the demands at each location and shipping rates. Solving the model, we get the results shown in Figure 24. The new network structure for this scenario. Since the Atlanta airport is shut down, the model chose the next best airport to minimize the overall network cost. From the options available, the next best airport was the Chicago airport.
Cost Analysis

The overall cost to operate the new network is 4.66 million USD instead of the 4.43 million USD previously. The net increase in the total cost of operating the network is +5%. It is not a substantial increase because the new airport is around the same distance from the distribution center.

Figure 25 shows the new cost distribution for each lane of the supply chain transportation. The cost of airfreight went up by 13%, but the road transportation - the cost of the airport to distribution center came down by 40%. Since the overall cost of air freight is significantly higher than road transportation, the overall cost of the network went up.
4.3.4. Scenario 2: Shutting Down Multiple Airports

In the previous section, we discussed a scenario in which a single airport near the distribution center is closed. Due to the availability of other airports, the model picked the next best airport that is closest to the distribution center to ensure continuity of the operation of the network.

In this scenario, we shut down all the airports near the distribution center – Louisville Distribution center. This is worst-case scenario enables us to understand the impact on the network if a distribution center is completely shut down from any air transport.

Using the application, we shut down all airports near the Louisville distribution center. We then solve the model. Figure 26 shows the new network structure. Since all the airports near Louisville are shut down, the next best option is to fly all the shipments to the Seattle airport. Then, the shipments are sent to the two distribution centers and delivered to the demand locations.

![Figure 26. Scenario 2 Network Structure](image)

**Cost Analysis**

For this scenario, the total cost of the network is 5.60 million USD. It is 26% higher than the optimal scenario and 20% higher than the previous scenario (single airport shutdown). Figure 27 shows the new cost distribution per shipment lane. The below cost distribution center shows an increase of 32% in airfreight while the rest of the cost per lane type remains similar to the previous scenarios.
4.3.5. Insights

The cost difference between the two scenarios (shutdown of one airport vs. multiple airports) is 20% of the total operational cost, i.e., 1.14 million USD. Suppose the current supply chain network rely on a single transshipment location for each one of its distribution centers. In that case, any potential disruption can cause a drastic increase in the transportation cost.

If the Louisville distribution center relies only on the Atlanta airport, then shutdown of that airport would mean the supply of goods is sent to the Seattle airport, increasing the transportation cost by 26%. However, due to the availability of other airports near the Louisville distribution center, such as Chicago Airport, the transport costs increased by only 5%. This shows that the availability of more than one transshipment location adds resilience to the overall network.

Additionally, in some worst-case scenarios, a single transshipment location can lead to a total breakdown of the network. Such as, for the above use case, if the origin airport was shut down, then the model will not find any route.

4.4. Use Case 2: Transportation Modes

Figure 28 shows the network structure of this use case. It shows all the involved nodes – The origin node (orange box) is located in Switzerland; it is connected to the distribution center (red
box). An airport (blue circle) is close to the distribution center. The warehouses (yellow triangle) are in Shanghai and Taipei; each demand point is connected to an airport (blue circle).

Figure 28. Use Case 2 Network Structure

4.4.1 Input Information

Figure 29 shows the yearly demand for the two warehouses. We see that there is high variability in demand throughout the year. Figure 30 shows the demand in units for each of the warehouses.
We see that 95% of the demand is focused on Shanghai, and the rest comes from Taipei. Figure 31 shows the demand in units of each product for the time period. We see that the product with the highest demand is product A, followed by product B.
4.4.2 Current Network Route

Due to the availability of airports only, the network has a single mode to transport the goods - Airfreight. The shipment is transported by road from origin node to the distribution center, then from the distribution center to the airport. Later, air freight is used to transport the shipment to the destination airports, followed by road freight to reach the warehouses. The figure 32 shows the network route after solving the model.

![Figure 32. Use Case 2 Optimal Route](image)

Cost Analysis

The total cost to operate this network is ~4.12 million USD. A cost of 4 million USD belongs to the air freight. Figure 33 shows that air freight accounts for 99% of the total cost, the rest 1% from road transportation (origin node to DC, DC to airport, and airport to the warehouse).

![Figure 33. Cost Distribution per Shipment Lane](image)
Figure 34 shows the cost distribution to ship each type of product. Product A costs 79.5% of the total cost, Product B costs 10%, Product E costs 4%, and the rest from products C and D.

4.4.3 Scenario 1: New Transportation Mode

In this scenario, we explore the idea of including additional modes of transportation. Given that Shanghai and Taipei are easily accessible by sea. Adding a sea route will bring more flexibility to the supply chain network and, in the long run, reduce the cost of transportation. Figure X shows the new network with the addition of the seaports (blue circles) for the supply and demand locations.

Figure 36 shows the new optimal solution. As transportation by sea is cheap, the model is shipping using the sea route.
The total cost of the new network is now 0.99 million USD compared to 4.12 million USD as per the base scenario. It is a reduction of 75.9% (3.13 million USD). Figure 37 shows the new cost distribution per shipment lane type, where sea freight represents 97% of the total cost.

**4.4.4 Insights**

The current network is overly dependent on a single transportation mode. By identifying new modes of transportation modes, we introduced flexibility to the network, thereby building resilience and reduced the overall cost of the network by ~76%.

**4.5 Discussion**

After understanding the results from the Use Case’s Data Analysis, Scenario Creation, and Cost Analysis we now discuss the results.
4.5.1 Analysis of the Results

As described in chapter 2, there are three ways to invest in building resiliency: redundancy, flexibility, and culture.

Redundancy: a resilient supply chain network has redundancies throughout the system. The organization can have additional inventory, many suppliers, etc. In use-case 1, we introduced redundancy by increasing the number of transshipment nodes (airports). During a disruption (shutdown of the primary airport), due to the availability of other airports near the distribution center, the increase in cost was only 5% (use-case 1: scenario-1). Without those airports, the increase in cost would be 26% (use-case 1: scenario-2).

Flexibility: Adding flexibility to a supply chain makes it resilient to withstand disruptions. It also provides strategic advantages to an organization. In use case 2, we used the strategic advantage of the demand locations (shanghai and Taipei warehouses) to explore new transportation modes – sea route. The use of sea freight can reduce the transportation cost by 75% provided the organization has accurate forecast data and has considered the lead-time involved with sea freight. By adding the flexibility to ship products using air freight and sea freight, the organization is resilient to possible demand/supply variations and reduce our transportation costs.

Culture: Culture is the essential factor in building a resilient supply chain network. It enables the long-term ability of the company to either be prepared for disruption or recover from one. Though we do not have quantitative results to show our application can impact company culture. From our demo with the organization, we received feedback that the application opens up communication across the employees. It acts as a collaborative tool to use during meetings/discussions. The application enables users to create disruption scenarios with ease and run a stress test to facilitate discussions backed with data.
4.5.2 Recommendations

The first recommendation for the multinational manufacturer is to increase the number of nodes. We saw the advantage of additional nodes in the literature review and the use-cases. In order to provide some candidate cities, we clustered the demand of the current network in clusters of 5 and 10. We then used a basic clustering algorithm to identify the best nodes (according to the popular cities) that fulfill all the demand while minimizing the distance from the nodes to each demand location (figure 38 and 39).

![Demand Locations - Cluster 5](image1.png) ![Potential Nodes - Cluster 5](image2.png)

Figure 38. Demand Location Clustering with \( n=5 \) and Candidate Cities

With the addition of the new nodes, we also need to understand the tradeoff between reducing risk vs. overestimating the likelihood of disruption. Investing in new nodes increases the operating cost of the network. Therefore, the organization must strategically add new nodes to make the supply chain resilient while understanding the likelihood of disruption to keep the optimal cost between supply chain performance and resilience.
The second recommendation is to decentralize the network. Figures 8, 9 and 10 show that the entire network relies on two central hubs in Europe (very close to each other). Any disruption around the central hubs will have a catastrophic effect on the entire network.

The third recommendation is to map more than one transportation mode for the demand locations (locations with demand above a particular minimum value). Currently, the network lanes are predominantly based on a single transportation mode. Adding the flexibility helps with possible disruptions and variation in demand/supply.
CHAPTER 5: CONCLUSION

The aim of this research is to assist leadership with building a resilient supply chain network. It does so by developing an interactive visual application to create potential disruption scenarios in the network. The application allows visualizing and measuring the effect of these scenarios. Therefore, allowing senior leadership to develop data-driven solutions in real life.

From the problem statement, we identify the need for a resilient supply chain network in this new era with many uncertainties. We find reports that show leadership being aware of the importance of a resilient network yet unable to act properly. After reviewing the available literature, it is clear that senior leaders face issues while making decisions to build a resilient supply chain due to the complex nature of the networks and lack of visibility. We also confirm the importance of interactive visualization in decision-making. Therefore, we have built an application able to create "what-if" disruption scenarios to assist with decision-making by visualizing the impacts in the network.

We test the application with data from the multinational manufacturer. We have created the first use case to demo the importance of redundancy in the network by understanding the impact of not adding extra transshipment nodes. The increase in cost for not having extra transshipment nodes is 21%. We create a second use case to measure the flexibility in the network in terms of available transportation modes. We have added a sea route to the lane that previously used only air freight. This has reduced cost by 76% and introduced flexibility in case of disruption.

The thesis’s main contribution is the ease for users to create any scenarios such as demand/supply variation, the shutdown of transshipment nodes for any geography, product, and period. Due to the ease of creating such scenarios using a simple UI, management can test multiple data-driven scenarios in a short period of time and create plans to avoid such disruption.
Lastly, our application drives culture change in an organization required to build resilience. It enables collaborative decisions making and provides clear transparency of the decisions made in the network during a disruption.

The current research can be extended in many ways. Firstly, the current model is limited to the data stored in the database. The model can be connected to the live data to use the latest information from the network. Secondly, the current model is a basic version of supply chain optimization. In the future, to create more kinds of scenarios, the model can be updated to include information such as the frequency of shipment, lead time for transportation, etc. Third, the next version of the application can have the ability to create new nodes using the UI for consideration for the optimization model.
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