RESILIENT SUPPLY CHAIN OPTIMIZATION

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ABSTRACT

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Especially after the COVID -19 the importance of studying the about resilient supply chain optimization has been increased even more. A supply chain network can be optimized with respect to many aspects such as inventory, supplier management and warehousing etc. In this study, the objective was to optimize the resilience in supply chain network with respect transportation cost and connectivity under different disruption scenarios. Since this study was based on hypothetical problem, after developing the relevant data, linear mathematical model and a mixed integer mathematical model was developed to achieve the research goal. The research modelling has done in two parts, where first part will solely focus on minimizing the transportation cost using linear mathematical model and in the second part minimizing transportation cost, considering the density of connections has been modeled using a mixed integer mathematical model.

The results of both modeling, along with sensitivity and scenario analysis shows that demand volatility has much more impact on the transportation cost compared to other disruption scenarios that was considered. It is further showed that compared to the original optimized model, the number of connections has been increased under the disruption but throughout the simulations the total number of connectivity remains to be unchanged. Overall, the thesis provides an idea about how the suggested solution would help the model to be more resilient.

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1 Introduction

1.1 Background of the Study

The introduction of the mass production and the popularity of line assembly was the foundation of supply chain management back in 1920s. while the concept supply chain was first introduced in 1905, it was not popular nor area that was much concerned until 1980s. (logmore.com, n.d.) Therefore, compared to some of the fields such as logistics, procurement is still considered as area that need improvement. (logmore.com, n.d.) As per the association for the professionals in supply chain management, the objective of supply chain management means, improve the customer's value through optimizing the systems and processes that take part in to fulfilling consumer demand while being profitable from the company point of view. Hence, studying about the methods to optimizing the supply chain has been a research area and also a professional area at the moment.

The design that a company or an organization that came up for as their supply chain network is a result of thorough learning and understanding of their market, options to choose suppliers or to build or rent warehouses and the processes. (logmore.com, n.d.) Hence slightest changes that we make to the network can impact in a major way in terms of cost is one of the main reasons, that a company needs to optimize their supply chain network.

Along with the rapid changes in the world in terms of technology, political, economic, and environmental wise, supply chain network is a sensitive area that can affect easily. For instances, in 1980s, the introduction of personal computers allowed to have more new techniques such as optimization models, algorithms which helps to predict logistics related problems in supply chain more effortlessly. (logmore.com, n.d.) As per the latest report by the Grand View Research, the global market size of the supply chain management is estimated to reach USD 37.41 billion by 2027. (logmore.com, n.d.) If we compare the market size of 2020, this is 11.2%

growth in the supply chain market. Further it states that the demand for more visible and transparent supply chain management along with usage of cloud-based supply chain management solutions are increasing rapidly. (logmore.com, n.d.)

Apart from the adaptation we should welcome to the supply chain network, due to new trends and requirements, it also very important that we should focus on more resilient supply chain due to the uncertainties that it faces. The most recent, memorable uncertainty or the disruption that the whole economy faced was COVID-19 had major impact on all the companies in a negative way mostly, which made them to find more suitable solutions and to focus on making their supply chain more resilience optimized. For instance, as per the survey conducted by Ernst & Young LLP US, (Harapko, 2023) in late 2020 to 2022, based on the senior level supply chain executives, they tried to evaluate the impact of COVID -19 on supply chain, and the plan for next years in terms of supply chain network. The key findings of this survey were that the pandemic had a solid negative effect on supply chain which reported 72% and this was divided into significant negative effect and mostly negative which were 17% and 55% respectively. Whereas only 2% of the companies were fully prepared for the scenario. The other key finding of the survey was the top priorities of the participated companies, which were better supply visibility, efficiency, and resilience. Few strategies that the survey has concluded are, re-structuring the supply chain network, build transparency and resilience, extracting cost from the supply chain, through agility growing the digital supply chain. Due to these reason, the need for resilient supply chain optimization is rising every day. As a resilient optimized network has the ability to mitigate the risks that involves, handle the disruptions more smoothly, helps to maintain the business continuity, maximize both customer satisfaction and resource utilization, it is needed to conduct more research on the subject.

1.2 Research Objectives and Questions

In terms of research areas, the supply chain optimization, resilience has been interested area for many years. There are numerous numbers of studies that has done separately on these topics and as a whole. There is much research that has been conducted in related these topics in terms of operation research, logistics and industrial engineering etc. where they have measured the resilience in terms of different formulas based on time or performance. But there are nearly no empirical studies that has been conducted where the resilience was measured in terms of transportation cost and the studies that has done with respect to minimizing the transportation along with maximizing the connectivity density are rarely to be found. Therefore, to fulfil this research gap, this thesis studies how supply chain can affect based several types of disruption scenarios, and what type of solutions that can be implemented for considered scenarios in order to enhance the resilience in terms of transportation cost based on hypothetical data structure. And further this study focuses on how to make the supply chain more resilient optimized. To achieve this goal, the following developed researched questions are to be addressed through this study.

1) Which disruption scenario has a major impact on the supply chain network in terms of transportation cost?

2) What are the most suitable solutions to enhance the resilience of the supply chain network in each scenario?

3) How can we make a resilient optimized supply chain network?

4) Based on the results, what are the other factors that need to be considered in order to maintain a resilience supply chain optimization?

In order to find the answers for the above research problems the modelling has been conducted under two parts by considering a hypothetical supply chain network is considered where it has 2 factories, 3 warehouses and 5 sales outlets. Here the capacities of factories and warehouses was assumed, along with the demand of each sales outlet. It is further assumed the routes of the original network and the transportation costs that involved. For the first part of the modelling, initially the optimized supply chain network was identified with the total transportation cost, later depend on four different disruption scenarios, the supply chain network was optimized and, the impact on the resilience was measured in terms of the percentage increased in the transportation cost. After evaluating the impact on the performance of the supply chain, different methods were implemented to enhance the resilience of the supply chain. Whereas, for the second part of the modelling, considered disruption scenarios were simulated n number of times and the network resilience was compared before and after considering the density of network. Other than finding the answers for the stated research questions, this study will contribute to the existing literature on resilience supply chain optimization through a comparison of diverse ways of evaluating the resilience in previous research work.

1.3 Research Limitation

As every research work faces limitation, in this study as well faced quite a few constraints. The main constraints were that this study is based on hypothetical scenario, hence when implementing the suggested solution for a resilience supply chain network optimization, it might require further study in that regard hence due to the industry the factors that need to consider would be vary. Even it is known fact that there can be many disruptions and uncertainties, here it is considered only 4 different scenarios for the analysis purposes. Further the assumption of considering only the transportation cost while assuming other cost remain constant can also be stated as a limitation of this study.

1.4 Chapter Outline

The dissertation consists of 5 chapters, where the next chapter, literature review would be about the studies that has conducted on supply chain network, optimization and resilience and the existing study gap in combine of all those topics. The third chapter methodology would discuss about the problems, considered hypotheses, mathematical model formulation of the study.

Under the fourth chapter the results are presented and finally the last chapter would discuss about the summarize of the obtained results and findings, areas need to be address in further studies.

2 Literature Review

Under the chapter two, literature review, a review of previous studies that related to resilient supply chain optimization has carried out. An empirical and theorical evidence that has been discovered by the other research are being presented for the key words separately and as a whole. The purpose of this chapter is to present the significant findings of the current knowledge. The goal of every supply chain network is to provide the right product, to the right customer at the right time with the minimum cost involved.

2.1 Supply chain network

The network that consists of suppliers, factories, warehouses, distribution centers and customers is considered as supply chain network, this network included all the activities that need to transform the raw material to end goods. (Misra, Khan, & Singh, 2010) Therefore, the main function of an effective supply chain network would be, product development, marketing, operations, distribution, finance, and customer service. (HAYES, 2023) And this would lead for an organization to have a faster production cycle at a lower cost. Every step taken to deliver a finished product or service to the consumer is included in the supply chain network.

As it shows in the below figure the process may involve acquiring raw materials, delivering them to the place of manufacturing, and then shipping the final goods to a warehouse or retail location where they may be distributed to the customer.

As we have a closely look at the functions that involved in supply chain management, it is clearly stated that all most all the significant functions of the company comes under that. For instances, the function that involves with purchasing the raw materials is one of the top functions that need to be control, hence we need to ensure that we purchase the raw materials at a certain price that will secure the final product value at marketplace while achieving the quality standard. Consequently, choosing the right supplier is a crucial decision.

While moving to the other component manufacturing, the company required to handle this process as it has impact on them economically as well as company's image wise. This step involves with the warehousing as well, hence the company is required to maintain the raw materials while the part of the production is being processed. And in this instance, we must make sure that the quality is not affected by the standard or the method of our warehousing. Plus, another aspect that need to re-assure is that the raw materials are being delivered on time for the production so that there will not be any delay in fulfilling the market demand. In contrary the company should also be aware that they do not possess any extra stocks which leads to have an additional expense.

Logistics or else distribution would be another component of the supply chain network. Delivering the final product safely while using the most cost-effective way is a decisive step. On the other hand, we need to make sure that we understand the risks that tangled in this stage so the company can prepare themselves ahead. With the current marketing trends such as, delivery on the same day as the order date, no return policy involved, the company needs to adapt a distribution method that will provide a good competition towards other rival companies. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.)

Therefore, at the end, the supply chain network is an integration of all the different kinds of flows within the company. Addition to this, there are several types of supply chain models that a company can acclimate. And this could be defined based on the goals and the specific needs that company is trying to cater.

Figure 1: Components of Supply Chain Network

2.2 Components of the Supply Chain Management

Under this sub chapter we are discussing about the seven components that support the supply chain management, namely those are, planning, information, sourcing, inventory, production, transportation and return goods.

Planning

Moving to the first component planning, it can take several types of planning that is associated with the supply chain, as it is stated in the following diagram. As it's seen the below figure each planning are inter-dependent of each other directly or indirectly. Based on the market demand,

Figure 2: Planning in Supply Chain Management

all the other related decisions of a company such as, raw material purchase, production, warehouse need can be arranged in a way better way. Hence, using techniques such as usage of historical data to predict the demand, would be much helpful for the organizations to forecast the demand and cater the follow up needs of the company. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.) Likewise, the company needs to make sure that supply planning, product planning and sales and operations planning also need to be done interactively with each other.

Sourcing

if the company is new one, then supplier selection can be a critical decision to be made, as it simply does not mean to pay our attention for the raw material purchase, since there are other factors that is been associated with our decision such as, the quality and price factors, flexibility of delivery, payment methods etc. as the first step towards the sourcing a supplier, the company needs to look up to the reputation and experience of the suppliers in the market if they do not have a prior knowledge in this area. The person who is responsible should be able to focus on whether the supplier can provide all the items or else as many items are required. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.)

Inventory

All the items that represent either the row materials or the finishes good or the good in process or the materials like packaging related goods can be considered as inventory. (KENTON, 2022) inventories considered as one of the important assets of the company as there is a turnover of inventory. And this would be the primary income generation method of the company. If the company is a service providing company, then the inventory for that organization would be tools and machines that required to perform the service.

Other than just maintaining the inventory the company is also must focus on, not maintaining the unnecessary goods in their warehouses as well. Because sometimes, the company might invest in the inventory that are not been used for the long time and because of this, it will create an excessive expenditure. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.)

Production

The process that converts the raw materials or components into finished goods so that there would be a value for the end user, or the customer is known as production. (Tomasetti, 2023) This would be dependent on the all the activities such as inventory, sourcing, and market demand. There are four main types of doing the production.

Figure 3: Different types of production method

Firstly, unit production is where the company produce one good at a time. These are the scenarios when the orders are being customizable. For instance, baking a birthday cake as per the pre-requisites of the customer would be a best example for the unit production. A business who follows unit production is highly dependent on the customer satisfaction.

Additionally, high-end businesses like Harley Davidson and Dell adopt this method of production. In fact, Harley Davidson offers a wide range of accessories that can be tailored to the user's preferences. Similar to this, we can use the provided specifications on the Dell website to construct our own laptop. (Bhasin, 2018)

Moving to the second type of the production, the batch production is considered as producing a set of identical goods at the same time rather than producing one good at a time. Depending on the demand or the order the manufacture will decide how many products are being produce in a one batch. And every time a batch has been produced the size of the batch can be different.

For instance, the collection of home appliance goods offered by LG is very diverse. It must produce all these various variations of the same kind of product. The product line of LG home appliances would include 10 to 20 different varieties of mixer grinders. As a result, a manufacturer like LG produces various versions in batches. (Bhasin, 2018)And this is considered as the most flexible production method which is most suitable for expanding small and medium scale businesses. (Pearson, 2021).

The third type of production method would be mass production which also known as flow production of series reduction. This is the ideal way to produce large number of identical products in a large quantity. (Team, 2020) There would be several assemblies' lines which specific functions to each line. Merchandise that are produced in big quantities are highly standardized.

Henry Ford invented the first assembly line method in 1913 for his renowned Ford Model T, which is considered to be the earliest instance of mass production. The effectiveness of the strategy allowed Ford to reduce the price of its cars. (Team, 2020)

Information

As the supply chain is a network that contributed by both internal and external parties, the flow of information plays a vital role. As the supply chain is a continuous process, even the information flow should be continuous and updated as without a well-maintained information system, any of the work won't be manageable properly. Most of the components that are a part of the supply chain network are either downstream or upstream, but the information is the only component of the supply chain that are necessary to be both downstream and upstream with the network. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.)

There are 3 main information types that are involved in supply chain network, which are:

1) Information offered by retailers

   Instances for these types of information would be feedback information, customer account and order information and any information that are related to market demand etc.

2) Information offered by manufacturers

   Information related to available stocks; order quantity would be the upstream information for suppliers. Whereas few exampled for the downstream information that comes from the manufactures to retailers would be production schedule, production timeline and planning, supply of resources.

3) Information offered by suppliers

   Time that takes to supply the goods, or the quantity of supplying would be few examples for information types under this category.

Figure 4: Upstream and Downstream entities in SCN

The supply chain network can be negatively impacted by information disclosure during the information exchange process. Not only will it prevent information from being shared, but it will also harm partnerships and the trust between the parties within the supply chain. (Yu & Wang, 2016) To obtain the information, an organization needs to bare a cost from the beginning of collecting the data, processing it and to share with other. Hence as a rational company, the organization needs to compare the benefits of the information sharing against the costs that involved in the process.

Transportation of Good

The basic process of the supply chain network is to make sure that the raw materials are being delivered to the manufactures on time and the final merchandises are to be delivered to end user on timely manner. Hence without transportation, there won't be any supply chain network within the company. Now a days it gradually becoming more expensive component of the supply chain network as the fuel prices are rising. As this plays main part in the production cost, it is mandatory for the company to explore more options for transportation to keep the competitive advantage within the market. Therefore, many present companies are employing different modes of transportation for different stages in the supply chain. (What Are The Important Components Of Supply Chain Management in 2022?, n.d.)

Figure 5: Role of transportation in SCN

Major factor that can help the company to figuring out the suitable transportation modes are a deep understanding about the customer behavior. That will help the company to adjust their priorities and to plan their shipments of the orders at a considerable transportation cost. Other than that, most businesses prefer to reduce transportation expenses by either increasing the quantity of cargo through economies of scale or by utilizing equipment to its fullest potential. (Cubitt, 2022)

If we looked into freight transportation, it is essential throughout the delivery process in supply chains, from carrying inventory to the producers, and to supplying the final product to the customers. The fact that transportation expenses normally account for between 2% and 5% of a company's revenues, while this percentage can be significantly greater for some industrial sectors, serves as more evidence of their significance. (Holcomb & Manrodt, 2000)

Supply chain and transportation are dyadically related. The demands of the supply chain are subject to transportation, but the way that function is run has the potential to change the character of these demands. In order to manage the supply chain effectively, it is crucial to comprehend both sides of this connection. (Potter, Towill, & Disney, 2007)

Return Goods

Delivering the final merchandise on time just won't be the end of the supply chain network, as a company, they should consider how they are planning to handle the returned goods if any. Having a proper return policy would affect positively for the brand name and for loyal consumers. Especially online retailers such as amazon, AliExpress, Shein follows a customer-oriented return policy. Most of the cased the cost of returning a product can be more costly than a producing and delivering a product for the first time as this involves certain more additional steps, such as gatekeeping.

And further that study concluded that maintain a return policy, discounts at wholesale prices are few more method that make the supply chain network to have a smooth functioning and to be flexible for unpredictable demand. (Sana, 2013)

Another study proposed to have a return policy between the retailers and the manufacturers in case goods are returned from the customer to retailer, to have it coordinated with the manufacturers as well. (Chen & Bell, 2011)

Another study examined a two layered supply chain that promoted the good return. The return of returned goods and the mechanism for storing open goods are the two stages of this supply chain. Using the geometric matrix method, to figuring out the ideal value of the maximum inventory capacity and the value of the acceptance decision, they investigate, assess, reduce the cost of the inventory system, and maximize returns from the production open process. (Aghaei & Zandi, 2012)

Another research promotes that both new and returned stock to be discounted during the seasonal period of the market, so both products are being sold at the same time. (Chen, Xue, & Yang, 2013)

A clear return policy should include duration of the return, conditions of the returns, exceptions, options for receiving the credits since it can be either cash receivables or store credits, time that taken to receive the payment, how to proceed the good return when the receipt is absent etc. (Tran, 2023).

The best way to handle the good returns would be trying to minimize it through understanding the reasons for returns. In order to handle just the authentic good returns, an organization can practice to use high quality images and the videos of the product, enabling the customers to leave a review, provide a detailed description of the merchandise, use high quality packaging, offering the customer support, improve the size chart, pay attention to the product improvement, identifying the pattern of order return to figure out the common error of the product and finally making sure the return process is also functioning smoothly from the customer end. (Tilleli, 2021)

2.3 Flows in Supply Chain

As it discussed under information in before chapter, other than the information flow, there are product flow, financial flow, value flow and finally risk flow that are incorporated with the supply chain network.

Product Flow

Moving the product flow, the parties that participating in here are vendors, manufacturers, warehouses, distribution agencies, customers. In general, product flow includes both raw materials and final merchandise that are being circulated with the supply chain. In case of the good return occurs, we can see a reverse direction of this flow.

Financial Flow

Same as the information flow, the financial flow has two directions. The downstream includes the cost and the investment. While cost be an expense to the supply chain, the investment is considered as the way of strengthening the network. Whereas the revenue that generated from the sales are flow inversely within the network.

Value Flow

The value flows are a downstream flow, where a value is being added to each stage of the supply chain network. Starting from the point where we purchase the materials to till the point reaches the end user, a value has been added and this accumulation of the values will determine the profits of the product.

Risk Flow

The risks that involved in the supply chain either can be internal or external risks. Sudden fluctuations in the market demand, environmental causes or a pandemic outbreak are some of the external risks that an organization can face. Whereas, employee strike, change in business structures or the process, machine break down are few examples of internal risks. Therefore, it is mandatory that the organization's supply chain should be flexible and be prepared to adapt any changes and recover as fast as possible for a smooth supply chain network.

Information Flow

The most important flow in the supply chain network is information flow as it needs to be on real time and any delay can cause a massive loss. Since the information need to be shared with both internal and external stakeholders, it is more exposed to face risks as well.

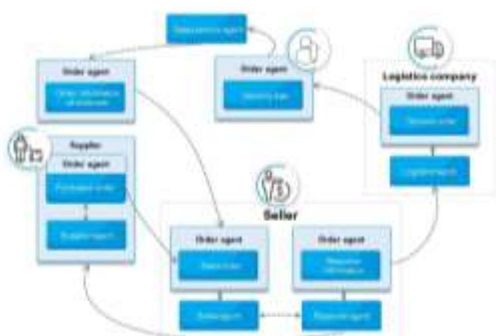


Figure 6: Downstream and Upstream Information Flow in SCN

2.4 Definition of Resilience

The term resilience has been derived from the Latin word "resilire". Resilire means to sprint back, to return. After the word resilience was added to the oxford dictionary in early 17th century, the word was first used somewhere around 1818 to describe a quality of wood by Tredgold. (McAslan, 2010). Later couple of decades, with respect to measure the quality of the materials that is being used for the royal navy ships the resilience concept was used by Robert Mallet.

(McAslan, 2010). As a result of Mallet's studies, he developed a concept called modulus of resilience, which measures the capability of the resources to resist to severe circumstances. This concept was used further in assessing the quality of the materials that is used in public buildings. For instance, the modulus of resilience explained the reason for why many houses and religious places were collapsed due to the great Neapolitan Earthquake in 1857.

As a concept, resilience means the ability to recover into the standard state, after facing disturbances to the process. Resilience also emphasis some other concepts such as awareness, detection, reaction etc. Resilience does not apply just for any industry; it is a concept that can be we can adapt in our life. For instance, how long a person would take to come back to his workplace after he faced a tragic incident or it might be the capability of a yarn to return to its earlier length after being overextended with a weight (Hoffman, 1948) or the ability of a farmer that can start to grow the vegetables after exposing to a plant disease can be couple of examples for resilience as in human's life and in the industry. (Drew, 2023)

Based on the definition we have for the resilience it can be different measures to evaluate it. (Carlson, et al., 2012) In general, the defining the resilience can be done only considering the after-event factors, considering both before and after event factors. The below mentioned are few examples for the definition of resilience that considered after event components.

- "Resiliency is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must" by (Allenby & Fink, 2005)

- "Resilience is the ability of system to absorb changes and still be persist" by (Holling, 1973)

- "The capacity of a system to survive, adapt and grow in the face of change and uncertainty" by (Fiksel, 2006)

  Whereas couple of definitions that describe resilience while considering both before and after dynamics can be presented as follows.

- “The term ‘resilience implies both the ability to adjust to ‘normal’ or anticipated stresses and strains and to adapt to sudden shocks and extraordinary demands. In the context of hazards, the concept spans both pre-event measures that seek to prevent disaster-related damage and post-event strategies designed to cope with and minimize disaster impacts” by (Tierney, 2003)

- “We see resilience as the aggregate result of achieving specific objectives in regard to critical systems and their key functions, following a set of principles that can guide the application of practical ways and means across the full spectrum of homeland security missions. The objectives of resilience that underpin our approach are resistance, absorption, and restoration” by (Allen, Kahan, & Thompson, 2009)

The most important difference between the two types of definition categories that is mentioned above is that the timing of actions that being taken to make the network or the system to be more resilient. Either the actions are taken prior to the event occur or after. Other than identified resilience as the ability to come to its original state, it can be also presented as the ability to reduce the possible failures or uncertainties, or it can be considered as the reducing the after effect of the event, or in some case reduce the time that is taken to recover. (Carlson, et al., 2012)

Having different interpretations of the resilience can be both advantages and disadvantages. Since along with the definition of resilience, the area that the resilience is being focused on, the measuring it can be vary. This would result a wide study area to conduct research on resilience and the same time having diverse concepts and its results may cause difficulties to compare the results.

Based on the objective of the study or the faced situation, different opinions and definitions can be formed to describe resilience, for instances, to explain system resilience or community. The table 1 indicates few definitions of resilience in different context. Based on the objective of the study or the faced situation, different opinions and definitions can be formed to describe resilience, for instances, to explain system resilience or community. The table 1 indicates few definitions of resilience in different context.

Table 1: Definitions of Resilience

Author	**Type of research topic**	**Definition**
(Luthar, Cicchetti, & Becker, 2007)	Ecological system	Dynamic process that has a result the positive adaptation in context of great adversity.
(Longstaff, 2005)	Ecological system	The ability by an individual, a group, or an organization to continue its existence in the face of some surprise.
(Masten, 2004)	Individual	A universal capacity which allows a person, group, or a community to prevent or overcome the damaging effects of adversity.
(Bonanno, 2004)	Individual	The ability of adult in otherwise normal circumstances who are exposed to an isolated and potentially highly disruptive event, to maintain relatively stable, healthy levels, of psychological and physical functioning.
(Norris, Tracy, & Galea, 2009)	Community	The ability of a community or a system to develop a series of adaptive capacity to recover from a disruption.
(Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008)	Community	The ability of community members to take meaningful and collective actions to remedy the impact of a problem, including the ability to interpret the environment, intervene and move on.
(Kessel, MacDougall, & Gibbs, 2014)	Organization	The intrinsic capacity of a system or society predisposed to a shock or stress to bounce forward and adapt to survive changing its non-essential attributes and rebuilding itself.
(Almedom, 2008)	Organization	The capacity of individuals, families, communities, and institutes anticipate, withstand, and judiciously engage with catastrophic events.

2.5 The growth of studies in Resilience

Resilience has become a steadily growing topic that are focuses on research since early 1980s. For instance, the number of researchers where resilience was a considered was nearly 60 papers back in 1993, whereas, by the time 2013 the number of research papers that was published that work with the term resilience is nearly 800. (Thoren, 2014) Regardless of the field, whether is it, history, material science, ecology, environmental studies, or sociology, conducting research with respect to resilience has been a significance research subject. (Thoren, 2014)

Early studies on resilience were mainly in the field of biology and material science, but recent studies shows that resilience has been a significant area that mention in reports and articles that been published by extremely influential organizations such as the International Monetary Fund and World Bank. Furthermore, in 1990s the resilience was emerging research topic in the field of textile research.

Starting even though the term resilience was used for studies in material science and environmental studies, later it was evolved into politics and liberal studies, hence policy makers and people in academic field was used the concept of resilience to re-write the laws, to establish research programs and resilience degrees. Currently many businesses school around the world has adapted resilience in their studies and advising the companies and organizations to taken resilience into consideration when they reform their strategies. (McAslan, 2010)

In the recent years the main reason for the popularity of the term resilience is because of the increased number of natural disasters, accidents related technology. As these causes has been affected for the existence of the people regardless of whether a country is a developing or a developed one. These natural or synthetic disasters has affected people significantly, causing them not being able to recover fully or recover faster from the disaster. And when it comes to the industries, it has affected the structure and functions in the same manner. Therefore, studying about the ability of a material to return to its original form of shape has come into the research area and that is known as resilience. (Carroa, Delgado, & González, 2019)

The organizational resilience was emerged with the speedy change in the business world. Since the businesses has to deal with the real time changes in the environment, organizations need to respond and react to those changes without any delay, the importance of the resilience was arising. Hence discussions and the research on the need of having a resilient eco system, understanding of the changing business external environment were more popular in back in 2003. (Hamel & Välikangas, 2003)

2.6 Supply chain resilience

One of the main growing concern due to the globalization would be supply chain resilience, as it is bound to be affected by the various types of disturbances. These conflicts required to have proper control, that can assist the supply chain resilient decisions. (Sidharath Joshi, 2022) Supply chains are becoming more layered and multi-dimensional with the resurgence of globalization as many companies amplify their network across the globe, leading to an increase in supply chain design parameters that involve a gigantic amount of data and are therefore exposed to various risks that lead to poor evaluation due to uncertainties, projection errors and inadequate analysis of modeling processes. (Li, Zobel, Seref, & Chatfield, 2019) Uncertainty creates an arbitrary environment for decision makers, forming it challenging to implement plans and make decisions about planning future events. The level of complexity is very high, if the uncertainty is modeled in the supply chain network. (Sidharath Joshi, 2022) In today's world, this uncertainty poses an extensive writing on the wall to the supply chain due to sophisticated trends such as globalization, outsourcing, just-in-time labor standards, vendor-managed inventory and lean practices, etc. (Pramudyo & Luong , 2019)

Uncertainties can be classified into major and minor ones, the ones that connected with strategic sources are considered to be major uncertainties on the other hand operational uncertainties are considered to be minor. These are further classified into 2 categories of based on the impact level which are high chance causing low impact (HCLI) and low chance causing high impact (LCHI). (Nezamoddini, Gholami, & Aqlan, 2019)

2.7 How resilience is being measured

The figure 7 is a graphical representation of the resilience in supply chain network. As per the image, the standard performance level is set at Q_0 and the process starts at time 0 till t_1. A disruption occurs at time t_0 which causes to the standard performance to drop till Q_1. During the time from t_0 to t_1, the disruption is being assessed and the recovery is being made gradually till it reaches the standard performance level of the network. (Li, Dong, Chong, & Kang, 2017)

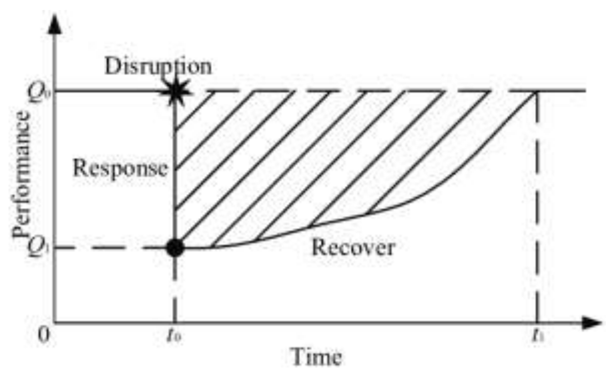


Figure 7: Graphical representation of Resilience

The triangle area refers to the loss of the performance due to the disruption or the uncertainty. This graph also shows the how the system functions after the disruption through the curve that started at time 0.

When we moved to the different measurements that can be used to evaluate the resilience of a network, we can list out few different measures as follows.

Table 2: Difference Resilience Measurements

Reference	**Measure**	**Formula**
(Li, Dong, Chong, & Kang, 2017)	This focus on the average normalized performance of the network, within the acceptable maximum regaining time after a disruption. Where t_0 is the time which disruption occurred, T_a is the maximum allowable recovery time.	$\mathbb{R} = \frac{\int_{t_0}^{T_a + t_0} Q(t)dt}{T_a}$
(Bruneau, et al., 2003)	Integration of the normalized performance function. Where t_0 is the time which disruption occurred and t_1 is the time the network reached its standard performance level.	$\mathbb{R}_{Loss} = \int_{t_0}^{t_1} [1 - Q(t)]dt$
(Cimellaro, Reinhorn, & Bruneau, 2010)	Integration of normalized performance function. Where t_0 is the time which disruption occurred and t_1 is the time the network reached its standard performance level.	$\mathbb{R}_C = \int_{t_0}^{t_1} Q(t)\, dt$
(Reed, Kapur, & Christie, 2009)	The ratio of the area under the performance curve and time interval that under consideration. Here $t_e - t_s$ is the time interval under consideration.	$\mathbb{R}_{ratio} = \frac{\int_{t_s}^{t_e} Q(t)dt}{t_e - t_s}$
(Zobel, 2011)	The ratio of the area beneath the performance curve to the strict upper bound of the recovery time (T^*).	$\mathbb{R}_Z = \frac{T^* - \frac{Q_1 T}{2}}{T^*}$
(Ouyang, Duen˜as-Osorio, & Min, 2012)	The ratio of the area between the actual performance curve P (t) and the time axis to the area between the target performance curve TP(t) and the time axis from 0 to T.	$\mathbb{R}_O = \frac{\int_0^T P(t)\, dt}{\int_0^T TP(t)\, dt}$

2.8 Optimization

In simple definition, optimization means, changing an existing process in terms of getting the best outcome while bounding to certain constraints. The outcome that we expect could be a maximum or a minimum value. For instance, our objective would be to finding out the best possible product mix that a company need to produce to either to get the maximum profit or to have the minimum cost.

Optimization has been used in many different fields for many years. Since the key goal in optimization is to find the feasible solution, this has been very useful in operational research, medicine, economics, management science, computer science, applied mathematics, engineering etc. (McKelvey & Neves, 2021)

Few of practical examples where optimization is being performed are, inventory management, budgeting, resource and production scheduling, market entry timing, product and marketing mix, supply chain planning, project or investment or loan portfolio planning. (LUMIVERO, 2023)

The concept optimization itself has opened its door to many research ideas, such as studies that carried out to find the optimal technology, new process, new designs. Optimization is a mathematical problem, that requires a set of methods and principals in mathematics. Because of the involvement of mathematic concepts in in optimization, in ancient times this is also known as mathematical programming. (Wright, 2023)

There are 3 basic concepts that associated with an optimization problem. Namely:

1) Objective function

This is the value or the output that a person trying to be optimized and it can be either minimized to maximized.

2) Variables

For the purpose of achieving the optimizing goal, the attributes that we can change are the variables. This could be labor hours or available raw materials.

3) Constraints

Constraints are the restrictions that associated with the variable that we can manipulate. Or else we can identify this as a condition that must fulfill through the process. For instance, the availability of raw materials can be limited or else the labor hours cannot exceed than a certain limit.

When it comes to solving an optimization problem, mainly there are 2 ways of programming that we can follow.

1) Linear programming

For instance, linear programming is a simple problem, that the goal is to either maximize or minimize the output that subjected to different constraints. Before the year 1947, the linear programming method was not commonly known concept. Following the second world war, especially in Europe and United States of America, this concept was becoming popular. By 1951, the interest in linear programming was spreading into other industries as well. As a method of solving linear programming problems, the simplex method which is also known as graphical method was introduced. But in practice there are thousands and hundreds of variables and constraints, this became not so efficient in using large scale problems.

2) Non – linear programming

If the objective function or constraint are non-linear, that is called as non-linear optimization problem. Feasible direction method, gradient projection method, multiplier method, bisection method and penalty function method can state as few examples for traditional ways to solve a non-linear problem (Onanaye, 2020).

2.9 Resilience in Optimization

Considering the definitions that we have discovered for resilience and the optimization; we can conclude that the resilience in optimization is how well an optimized network or a solution or a system can respond or adapt during a disruption scenario. Here the objective would be to continue to make the system optimal regardless of any external shocks or any uncertainties that can occur.

resilience in optimization aggregates lots of principles and concepts and also these can be identified as the resilience infrastructures, such as robustness, response and recovery and Contingency Planning can be stated as few principles that related to resilience in optimization.

For instance, the concept of contingency planning refers to having the back up plans in case of a disruption. As an example, in when it comes to the public health sector, maintaining an emergency responses system would increase the disaster resilience along with allaying the possible consequences. Quick activation of these back up plans would assist to maintain a fast optimized models. (Sampson, Akwafuo, Mikler, & Fariba, 2020) Another reason that it is advantageous to have a contingency planning would be to avoid the complexity of the models or the system that is cause by the disruption. As per the article that was published by the United Nations foundation, their usual way of fulfilling the country requests by placing the orders by long-term clients was affected drastically due to the COVID -19, along with the trade restrictions, closed boarders were causing so much complexity in their supply chain network. (ALAOUI, 2020). Plus, the properly developed contingency planning will help with the system's or a network's recovery, reconstruction and rehabilitation. (Ohara, Nagumo, Shrestha, & Sawan, 2018). As per the study that has done by (Ohara, Nagumo, Shrestha, & Sawan, 2018) it is identified that for a proper contingency planning we need to,

1. Understand the current conditions or the situation.
2. Identify the risk or the uncertainties
3. Analyzing the impact
4. Develop response strategies
5. Develop the final contingency plan

The next related principle in resilience in optimization would robustness. As we identified resilience as the ability of a system to recover after facing an uncertainty, whereas the robustness would be the ability to withstand or cope up with the uncertainty. If couple of examples give for two concepts where it can be more clarified in a simple way, the during the time of COVID-19, mostly the healthcare organization were able to continue to provide their services, which is an example for robustness. On the other hand, due to the pandemic, the tourism industry was affected significantly but was recovered after certain time, which is an example for resilience. (Munoz, Jon Billsberry, & Ambrosini, 2022). The more sensitive the network would be, it will help to maintain the robustness of the network and it will be more resilience in optimization. This sensitivity of the network can also be identified as variation of the performance of the network. Hence along with the high robustness, the network would be able to stand up for uncertainty and resist the negative impact on the business. (Munoz, Jon Billsberry, & Ambrosini, 2022)

The next principle that are in collaborated with resilience in optimization is response and recovery can be considered as significant components as it is focus on how effective the company's response strategies and how quickly the organization can manage to go back to its standard network. As per the old saying which, "Best defence is a good defence", having the proper response strategies will mitigate the negative impact on the system. Having a contingency planning, prioritizing critical activities, scenario and sensitivity analysis can be few examples for a response strategy that can help the company, because in the most practical cases of supply chain network or any other system, most of the time the people who are responsible are supposed to make real-time decisions so the company can secure their profits as much as they can during a disruption time. On the other hand, thein a case the response strategies were not able to withstand the disruption, the company can look into some other options such as re-structuring the network, adapting new conditions as their recovery mechanism.

Based on the understanding of the principles that are a part of the resilience in optimization, we can conclude that those principles are inter-related and inter-dependent. For instance, having a good contingency plan would make the company to have a good response strategy, and hence it will increase the robustness and resilience along with being able to stay with the optimal level.

3 Methodology

In this chapter, will be discussing about the methods and procedures that are being used in this study. Under this section, will be describing, problem statement, the model objective function, model assumptions or constraints, the variables that involved, and mathematical model formulation.

3.1 Problem Statement

The objective of this study is to identify different disruption scenarios that can affect the supply chain and evaluate the resilience of the supply chain in terms of cost. Hence there are many factors that can cause a significant impact on the supply chain, such as

1) Demand variability due to market conditions, seasonal effect
2) Inventory management as it changes according to the demand and supply changes
3) Supply disruption mainly due to transportation issues, natural disasters, geopolitical events
4) Lead time variability as it affected by delays in production, transportation and customs
5) Cost considerations. Since there should be a balance in between the resilience and cost that involved with a resilient supply chain network such as transportation cost, inventory cost etc.

Under this study we are considering 3 different disruption scenarios and will be evaluating the resilience time and cost that involved with that. And finally, will be modelling a multiple disruption scenario to assess the resilience. The considered disruption scenarios would be,

1) Demand volatility:

In here we are trying to assess the resilience when there are sudden changes in customer demand. This could be increasing or decreasing the demand for all the customers at once or just for few customers.

2) Transportation network failure:

Here we will be evaluating how the transportation network is being affected may be due to a natural or an artificial cause and how it would impact for the transportation cost and delivery time of the products.

3) Supplier failure/Supplier shutdown:

Under this disruption scenario, we are trying to simulate reduction in the supply due unexpected events.

The hypothetical data that was considered for this study is a situation where a company that has two factories, with 3 warehouses and 5 different sales outlets. And here we considered the distances between each node to minimize as our objective function.

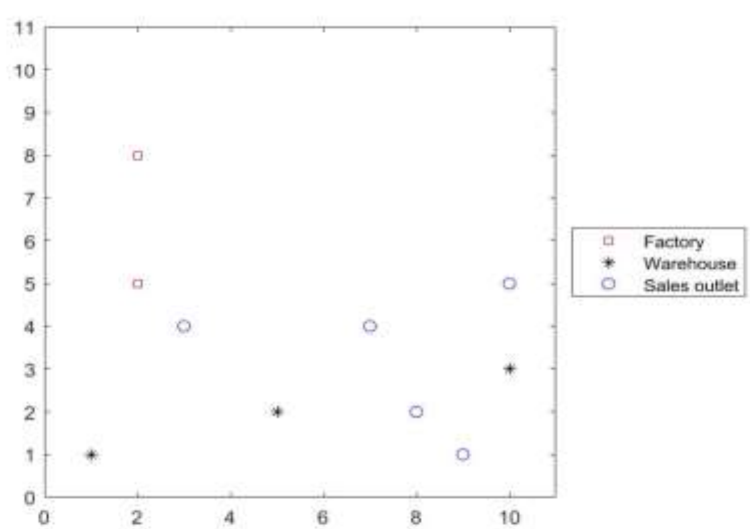


Figure 8: Hypothetical Supply Chain Network

Table 3: Total transportation cost from factories to warehouses

From / To	Factory one	Factory two	Total Warehouse Capacity
Warehouse 1	7	6	2,500
Warehouse 2	5	4	5,000
Warehouse 3	8	9	7,000
Total Factory Capacity	10,000	8,000	

Table 4: Transportation cost from warehouses to sales outlets

	Warehouse 1	Warehouse 2	Warehouse 3	Total Demand
Outlet 1	5	6	7	2,000
Outlet 2	4	3	3	800
Outlet 3	8	10	9	2,500
Outlet 4	5	5	4	4,000
Outlet 5	10	7	12	2,100

3.2 Modelling

The model formulation of this thesis has been done under 2 sections where the first part of the modelling focuses on minimizing the transportation cost solely and comparing the effect on the transportation cost under 4 different disruption scenarios with the standard optimized model. Here the objective is achieved through linear programming.

Whereas the second part of the model’s has two objectives where one would be the minimizing transportation cost along with maximizing the connectivity of the nodes through multilinear programming.

3.3 Model Formation – first part

As per considered data for this study, our step towards the model formation would be identifying the decision variables.

Decision Variables

X_{ij} = the number of units from transported from factory to warehouses. Here, i would be the number of factory and j would be number of warehouses.

Y_{jk} = the number of units, transported from warehouses to sales outlets. Here, j would be the number of warehouse and k would be number of sales outlets.

Objective Function

Our goal of this study is to determine the resilience of supply chain optimization. As the next step of the model, we are building the objective function which is to minimize the transportation cost. This would be the case when there is no disruption. Later in this chapter we will be modifying our model based on few disruption scenarios that has mentioned early in this chapter.

$$\min \left(\sum_{i=1}^{n} \sum_{j=1}^{m} aX_{ij} + \sum_{j=1}^{m} \sum_{k=1}^{s} \beta Y_{jk} \right) \qquad (1)$$

Where:

- n: the number of factories
- m: the number of warehouses
- s: number of sales outlets
- α: cost to transport goods from factories to warehouses
- β: cost to transport goods from warehouses to sales outlets
- i: the number of factories
- j: the number of warehouses
- k: the number of sales outlets

Subject to:

- $\sum_{j=1}^{m} X_{ij} \leq \ i^{th}$ Factory Capacity that been distributed among total warehouses
- $\sum_{k=1}^{s} X_{jk} \ \leq j^{th}$ Warehouse Capacity that has been distributed among total sales outlets
- $\sum_{i=1}^{n} X_{ij} = \sum_{k=1}^{s} Y_{jk}$, Total goods received by jth Warehouse should be equal to the total number of goods distributed among by all the sales outlets.
- $\sum_{\boldsymbol{j=1}}^{\boldsymbol{k}} S_j \ = Demand_s$, Where we need to derive this for each outlet
- $X_{ij}\ _{,}\ Y_{jk} \geq 0, for\ all\ i, j\ and\ k$

Resilience in terms of Transportation Cost

To measure the impact on the supply chain network's performance or in other words to make the supply chain network more resilient, it is decided to measure the change in the transportation cost by comparing the change total transportation cost after disruption with the original cost.

$$Cost\ to\ make\ SCN\ Resilience = \frac{(Transportation\ Cost\ under\ standard\ situation - Transportation\ Cost\ under\ disruption\,)}{Transportation\ cost\ under\ standard\ situation}$$

3.4 Hypothetical Problem

As it mentioned above, here we are determining the default supply chain network and assess the transportation cost, where we assume no disruption scenarios. Later in this chapter will be focusing on different disruption scenarios and assess the resilience in terms of transportation cost, and the ability of the network to self – operate. And later will be assessing how different suggestions would help the supply chain network to enhance its resilience.

For the hypothetical data that we are considering above, the derived we have built the objective function, constraints as below.

Objective Function

$$Min \quad 7X_{11} + 5X_{12} + 8X_{13} + 6X_{21} + 4X_{22} + 9X_{23} + 5Y_{11} + 4Y_{12} + 8Y_{13} + 5Y_{14} + 10Y_{15} + 6Y_{21} + 3Y_{22} + 10Y_{23} + 5Y_{24} + 7Y_{25} + 7Y_{31} + 3Y_{32} + 9Y_{33} + 4Y_{34} + 12Y_{35}$$

Constraints

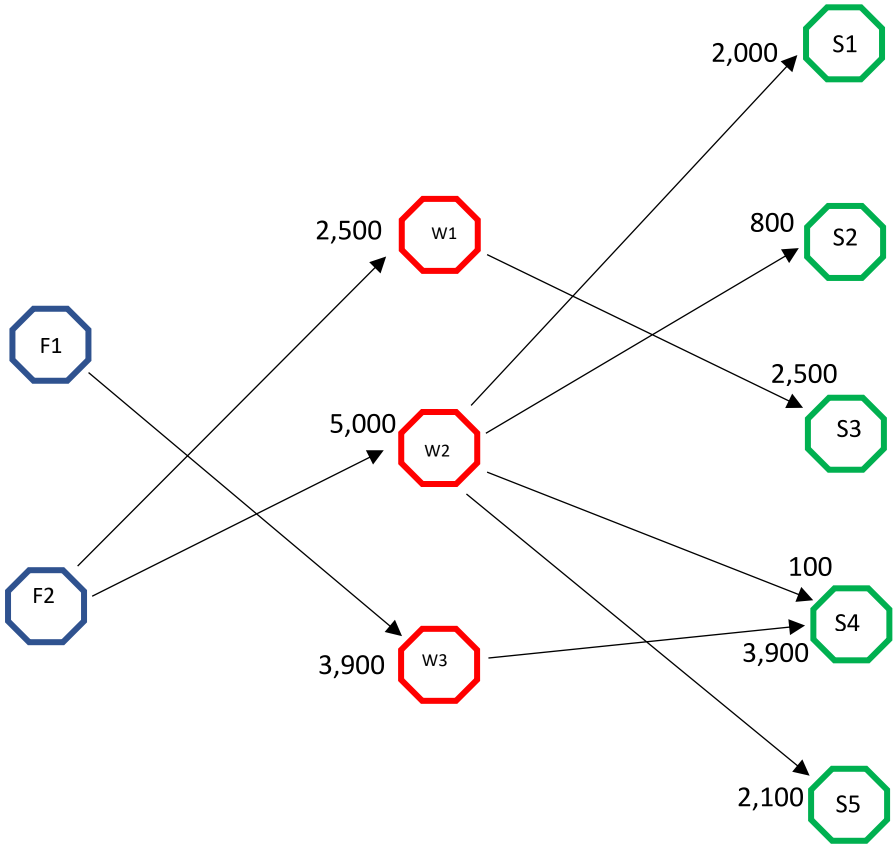
1) $X_{11} + X_{12} + X_{13} \leq 10{,}000 \quad (Capacity\ to\ produce\ at\ factory\ 1)$
2) $X_{21} + X_{22} + X_{23} \leq 8{,}000 \quad (Capacity\ to\ produce\ at\ factory\ 2)$
3) $X_{11} + X_{21} \leq 2{,}500 \quad (Capacity\ at\ Warehouse\ 1)$
4) $X_{12} + X_{22} \leq 5{,}000 \quad (Capacity\ at\ Warehouse\ 2)$
5) $X_{13} + X_{23} \leq 7{,}000 \quad (Capacity\ at\ Warehouse\ 3)$
6) $X_{11} + X_{21} - Y_{11} - Y_{12} - Y_{13} - Y_{14} - Y_{15} = 0$
   $(Prooducts\ at\ warehouse\ 1\ is\ being\ distributed\ to\ all\ the\ sales\ outlet)$

6) $X_{12} + X_{22} - Y_{21} - Y_{22} - Y_{23} - Y_{24} - Y_{25} = 0$
   $(Prooducts\ at\ warehouse\ 2\ is\ being\ distributed\ to\ all\ the\ sales\ outlet)$

7) $X_{13} + X_{23} - Y_{31} - Y_{32} - Y_{33} - Y_{34} - Y_{35} = 0$
   $(Prooducts\ at\ warehouse\ 3\ is\ being\ distributed\ to\ all\ the\ sales\ outlet)$

8) $Y_{11} + Y_{21} + Y_{31} = 2{,}000 \quad (Demand\ by\ outlet\ 1)$
9) $Y_{12} + Y_{22} + Y_{32} = 800 \quad (Demand\ by\ outlet\ 2)$
10) $Y_{13} + Y_{23} + Y_{33} = 2{,}500 \quad (Demand\ by\ outlet\ 3)$
11) $Y_{14} + Y_{24} + Y_{34} = 4{,}000 \quad (Demand\ by\ outlet\ 4)$
12) $Y_{15} + Y_{25} + Y_{35} = 2{,}100 \quad (Demand\ by\ outlet\ 5)$
13) $X_{ij}\ ,\ Y_{jk} \geq 0, for\ all\ i, j\ and\ k$

After optimizing the standard problem, the optimized supply chain network is as follows.



As per the standard optimized model, neither of the factor capacity has not been fully used. Factory 1 contributes by 3900 units and factory 2 contributes by 7500 units. But if we assess the warehouse capacities, both warehouse 1 and 2 has been utilized fully. Under optimized supply chain network, the transport cost that has to incur would be 131,400.

Disruption Scenario 1

For the 1st scenario will be assuming a volatility in demand in one outlet and volatility in demand for all the outlets. The change in demand is as follows.

- Outlet 1 – demand increased from 30% (Hence the new demand is 2,600 units)
- Outlet 2 – 50% demand increased (New demand 1,200)
- Outlets 3 – demand reduced by 100 units (New demand 2400)
- Outlet 4 – demand increased by 20% (New demand 4,800)
- Outlet 5 – no change in demand

Disruption Scenario 2

Transportation failure would be the 2nd disruption scenario that will be considered. And in this hypothetical case, we assume that the route from factory 2 to warehouse 1 is no longer working along with from warehouse 1 to outlet 3 route is no longer working while factors are remained unchanged.

Disruption Scenario 3

Under this hypothetical disruption scenario, we assume that the capacity of the factory and warehouses has been affected due to artificial cause.

- Factory 2 capacity has reduced by 50%
- Warehouse 1, new capacity is 2,000
- The new capacity of the warehouse 2 is 3,500
- The warehouse 3 capacity has reduced by 1,000

Disruption Scenario 4

The last disruption scenario deals with all 3 disruption scenarios that we implemented earlier. Hence here we assume demand volatility, supplier shutdown, and failure in transport network all at once.

- Factory 2 capacity has reduced by 50%
- Warehouse 2 capacity has reduced by 1,000 units
- 200 units demand increment in sales outlet 2
- Demand of sales outlet 3 reduced by 500 units
- 1000 units increased in demand from the sales outlet 4
- 400 unit increase in demand by sales outlet 5
- The route from factory 2 to warehouse 2 doesn't work and the route from warehouse 2 to the sale outlet 2 doesn't work either

Suggested solution

1) Introducing new routes to the supply chain
2) Enhanced capacity for factory or warehouses or both together.
3) Alternative transport method service.

3.5 Model Formation – second part

Under second part of the model formation, here it is considered 2 different disruption scenarios which are,

1. Demand volatility
2. Reduction in Supply Capacity

And will be trying to minimize our transportation cost along with maximizing the nodes under several simulations and evaluate how it will impact our overall network performance. Here the pervious objective function was modified with an addition of penalty term that relates to the number of the connections in the network. The goal of the addition of the penalty term was to reduce the value of the objective function as the number of connections increases.

Hence under the model formation part two, initially the effect of each disruption on the transportation was calculated and it will be compared with the function which has the addition of the penalty and see how the old objective function has changed under different scenarios and the percentage of the change also be evaluated.

Addition to the Decision Variables

Apart from the decision variables that discuss under part 3.3, a new decision variable Z_{ij} and U_{jk} were introduced. Where.,

- Z_{ij} : Usage of the route from i^{th} factory to j^{th} warehouse, where the values of Z_{ij} would be binary
- U_{jk} : Usage of the route from j^{th} factory to k^{th} warehouse, where the values of U_{jk} would be binary, as these would be indicating the either the route was used or not.

Objective Function

With addition of the new decision variables, the objective function will be updated as follows.

$$\min \left(\sum_{i=1}^{n}\sum_{j=1}^{m} aX_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{s} \beta Y_{jk}\right) - C.\ \left(\sum_{i=1}^{n}\sum_{j=1}^{m} Z_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{s} U_{jk}\right) \tag{2}$$

Where:

- n: the number of factories
- m: the number of warehouses
- s: number of sales outlets
- α: cost to transport goods from factories to warehouses
- β: cost to transport goods from warehouses to sales outlets
- Z: binary variable to indicate the route usage from factory to warehouses
- U: binary variable to indicate the route usage from warehouse to sales outlets
- i: the number of factories
- j: the number of warehouses
- k: the number of sales outlets

The considered constraints and the hypnotical problem that was referred in model formulation part one would apply here as well. Other than the existing constraints, the second part of the modelling also add new set of constraints as follows.

Subject to;

- $X_{ij} \leq i^{th}\ Factory\ capacity * Z_{ij}$, where X_{ij} is the number of goods that been distributed from factory i to warehouse j. We need to formulate this for each route.
- $X_{ij} \leq j^{th}\ Warehouse\ capacity * Z_{ij}$, where X_{ij} is the number of goods that been distributed from factory i to warehouse j.
- $Y_{jk} \leq j^{th}\ Warehouse\ capacity * U_{jk}$, where Y_{jk} is the number of goods that been distributed from warehouse j to sales outlet k .

- $C.\ (\sum_{i=1}^{n}\sum_{j=1}^{m} Z_{ij} \ + \ \sum_{j=1}^{m}\sum_{k=1}^{s} U_{jk}\ )$ is the penalty term, where is a constant.

Additional Constraints for route selection

1) $X_{11} - 10{,}000\, Z_{11} \leq 0\ (Route\ selection\ from\ Factory\ 1)$
2) $X_{12} - 10{,}000\, Z_{12} \leq 0$
3) $X_{13} - 10{,}000\, Z_{13} \leq 0$
4) $X_{21} - 8{,}000\ Z_{21} \leq 0\ (Route\ selection\ from\ factory\ 2)$
5) $X_{22} - 8{,}000\, Z_{22} \leq 0$
6) $X_{23} - 8{,}000 Z_{23} \leq 0$
7) $X_{11} - 2{,}500\, Z_{11} \leq 0 (Route\ selection\ to\ receive\ goods\ by\ warehouse\ 1)$
8) $X_{21} - 2{,}500\, Z_{21} \leq 0$
9) $X_{12} - 5{,}000\, Z_{12} \leq 0\ (Route\ selection\ to\ receive\ goods\ by\ warehouse\ 2)$
10) $X_{22} - 5{,}000\, Z_{22} \leq 0$
11) $X_{13} - 7{,}000\, Z_{13} \leq 0\ (Route\ selection\ to\ receive\ goods\ by\ warehouse\ 3)$
12) $X_{23}\ 7{,}000\, Z_{23} \leq 0$
13) $Y_{11} - 2{,}000\, U_{\ 11} = 0 (Route\ selection\ to\ receive\ goods\ by\ Sales\ outlet\ 1)$
14) $Y_{21} - 2{,}000\, U_{21} = 0$
15) $Y_{31} - 2{,}000\, U_{31} = 0$
16) $Y_{12} - 800\ U_{12} = 0 (Route\ selection\ to\ receive\ goods\ by\ Sales\ outlet\ 1)$
17) $Y_{22} - 800\, U_{22} = 0$
18) $Y_{32} - 800\, U_{32} = 0$
19) $Y_{13} - 2{,}500\, U_{13} = 0\ (Route\ selection\ to\ receive\ goods\ by\ Sales\ outlet\ 1)$
20) $Y_{23} - 2{,}500 U_{23} = 0$
21) $Y_{33} - 2{,}500 U_{33} = 0$
22) $Y_{14} - 4{,}000\, U_{14} = 0 (Route\ selection\ to\ receive\ goods\ by\ Sales\ outlet\ 1)$
23) $Y_{24} - 4{,}000\, U_{24} = 0$
24) $Y_{34} - 4{,}000\, U_{34} = 0$
25) $Y_{15} - 2{,}100\, U_{15} = 0\ (Route\ selection\ to\ receive\ goods\ by\ Sales\ outlet\ 1)$
26) $Y_{25} - 2{,}100\, U_{25} = 0$
27) $Y_{35} - 2{,}100\, U_{35} = 0$
28) $X_{ij\ ,}\ Y_{jk} \geq 0, for\ all\ i, j\ and\ k$

29) Z_{ij} and U_{jk} are $binary$

30) $C = 500$

Disruption Scenario 1

Under this scenario we assumed the increase in demand of outlet 1 and 3 separately, and further we are considering the to simulate to the demand increment from 10% to 50% for sales outlet 1 where the increment is 2% and for the sales outlet 2, the demand increment from 10% to 60% with 2.5% increment at a time step.

Disruption Scenario 2

For the disruption scenario 2, we assume the capacity reduction in the factory 2 and warehouse 2. In here it assume the capacity reduction is by 5% would be from 10% to 40% for both facilities.

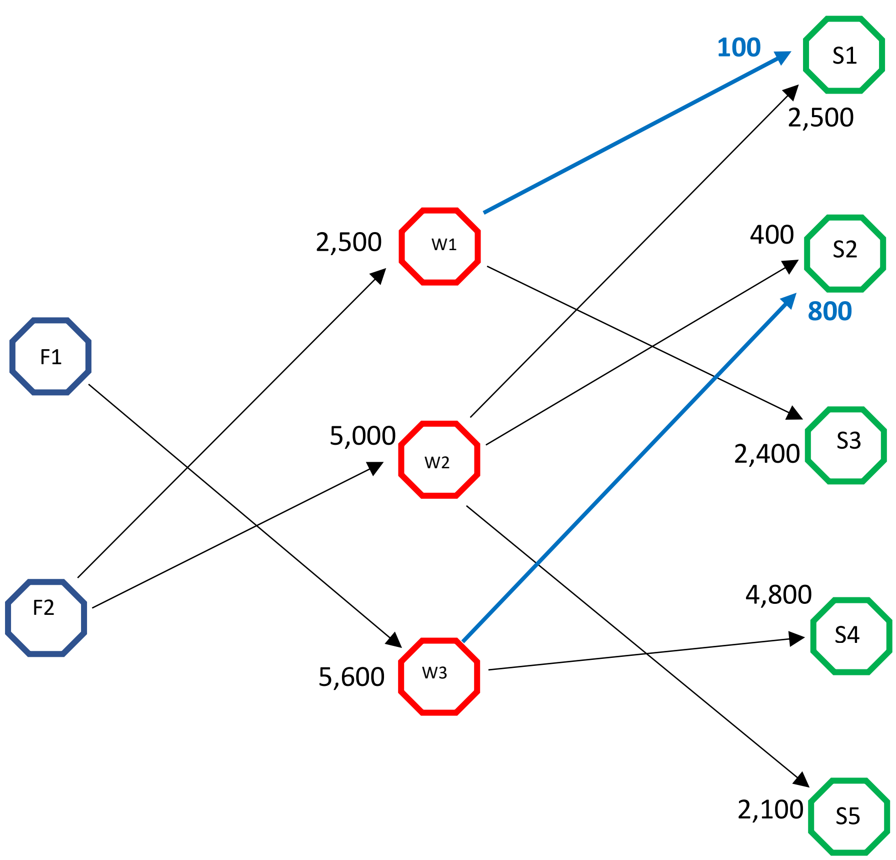
4 Result Representation

In this chapter, will be presenting the impact to the supply chain network and to the transportation cost under different disruption scenarios and evaluate how it has affected for the resilience. And how the suggested solutions have made an influenced to the supply chain network.

4.1 Results from Model I

4.1.1 Disruption Scenario 1

Due to the disruption, the capacity usage of factory 1 and warehouse 3 was increased, which lead to replacing two transport routes instead of one route. And after the disruption, the new cost of the transportation is 152,000.



The resilience was calculated in terms of transportation cost as follows.

$$Extra\ cost\ in\ Transportation = \frac{(Transportation\ Cost\ under\ standard\ situation - Transportation\ Cost\ under\ disruption\ )}{Transportation\ cost\ under\ standard\ situation}$$

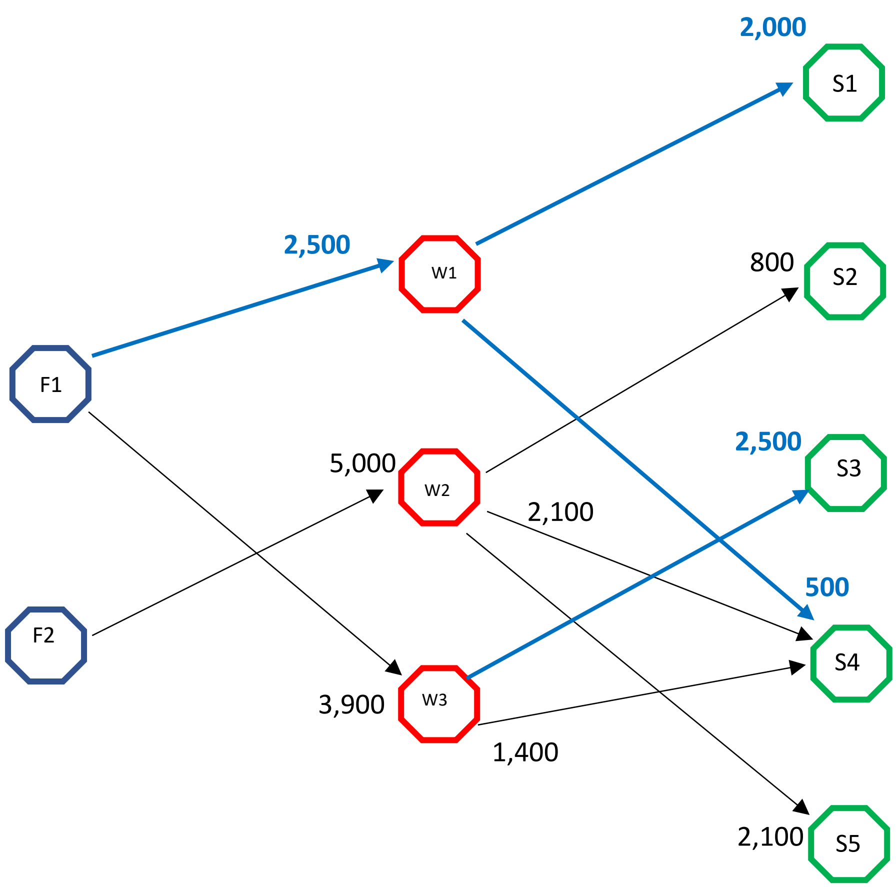
$$Extra\ cost\ incurred\ to\ make\ the\ network\ more\ resilient = \frac{(131{,}400 - 152{,}000)}{131{,}400}$$

$$= -0.15$$

Under the scenario one, the resilience value is negative 0.15, which indicates that when the supply chain network affected by the given demand fluctuations, it causes the transportation cost to rise by 17%.

4.1.2 Disruption Scenario 2

The updated supply chain network after facing the disruption 2 is as follows.



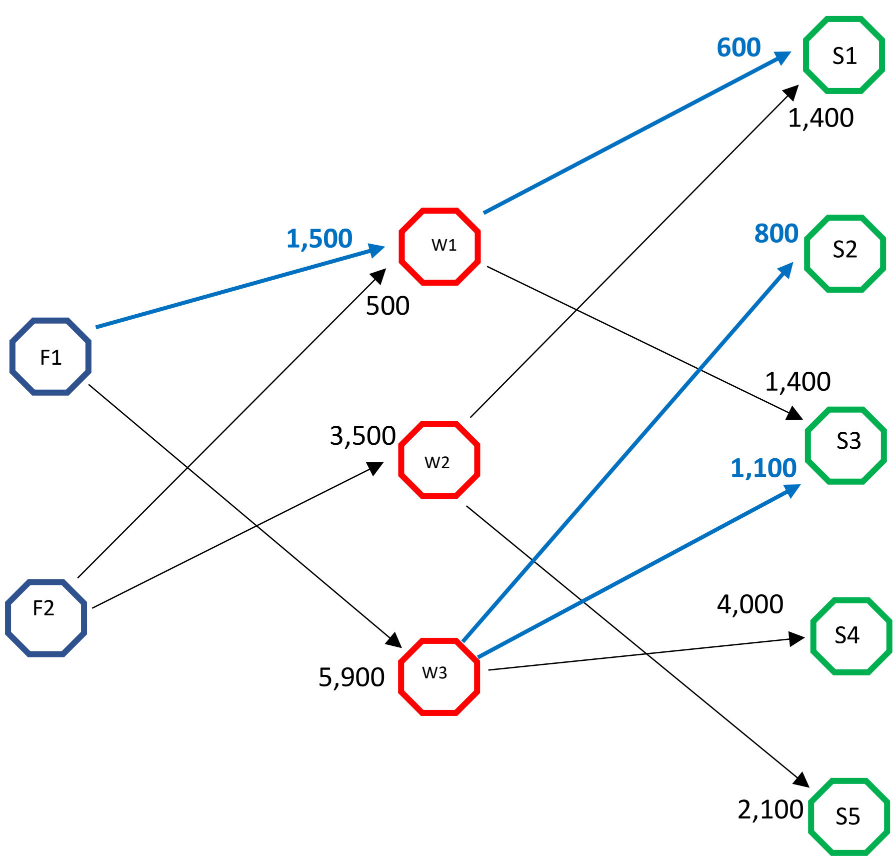
As per the updated network, instead of the routes F2 to W1, the warehouse 1 was received its goods from factory one and demand of the outlet 3 was fulfilled from warehouse 2 and some portion of the demand of outlet 4 was fulfilled from warehouse 1, which is 500 units. At the end, the optimized transport cost under disruption scenario 2 is, 136,900.

And to check the cost that incurred to make the supply chain resilient, it was calculated as follows and it indicates that there is 4% rise in original transportation costs when it self-operated.

$$Extra\ cost\ incurred\ to\ make\ the\ network\ more\ resilient = \frac{(131{,}400 - 136{,}900)}{131{,}400}$$

$$= -0.041$$

4.1.3 Disruption Scenario 3



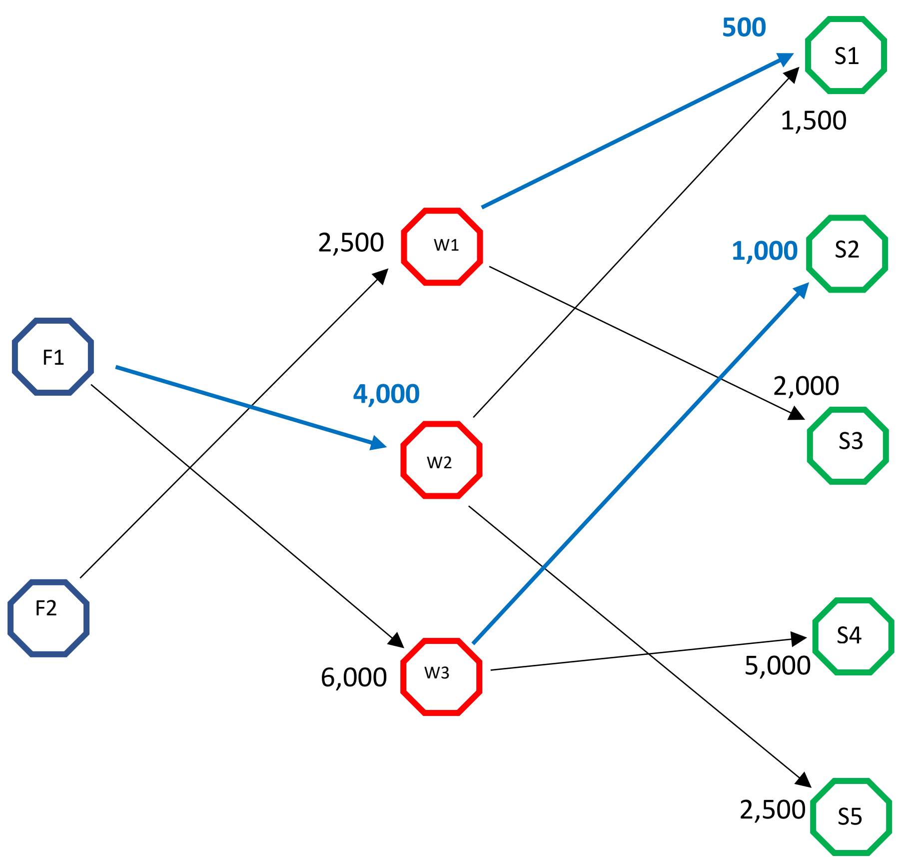
As per the updated supply chain network above under disruption scenario 3, to make the supply chain network run smoothly the company has to increase their transportation by nearly 7% and has to find alternative routes. Compared to the original network, we can see that there are 4 new mapping has been used to optimize the network under change of capacity at factory and warehouses.

$$Extra\ cost\ incurred\ to\ make\ the\ network\ more\ resilient = \frac{(131{,}400 - 140{,}300)}{131{,}400}$$

$$= -0.067$$

4.1.4 Disruption Scenario 4

The updated supply chain network as per the disruption scenario 4 would be as follows.



As per the resilient supply chain network, in order to make up for the route that does not work from factory 2 to warehouse 2, a new route from factory 1 to warehouse was introduced and warehouse 2 capacity was occupied with 4000 units of goods, further compared to the original supply chain network, a route from warehouse 1 to sales outlet 1 and from warehouse 3 to sales outlet 2 was created as a remedy for the disruption scenario 4. But in terms of additional cost that need to incur for the transportation cost for this optimized network is calculated below.

$$Extra\ cost\ incurred\ to\ make\ the\ network\ more\ resilient = \frac{(131{,}400 - 151{,}000)}{131{,}400}$$

$$= -0.149$$

4.1.5 Introducing new routes

As the first suggestion to improve the resilience of the network, it is suggested that to use of new routes. Compared to the original network, there are no direct routes from the plants to sales outlets. Hence, as a resilience measure introducing new routes is evaluated here under 2 different stages and the impact on the supply chain network is measured.

In order to determine the transportation cost from factory 1 to sales outlets directly, the calculations were proceeded as per the table 5. Further the respective S_i values that refers in the table 5, was taken from the above-mentioned table 4. The same process was used to determine the direct transportation cost from factory 2 to sales outlets that represent in table 7 below.

1. Introducing direct routes from factory 1 to all sales outlets.

Table 5: Transportation cost from Factory 1 to Sales Outlets

Sales Outlet	If $F_1 \rightarrow W_1 = 7$, then $F_1 \rightarrow W_1 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	If $F_1 \rightarrow W_2 = 5$, then $F_1 \rightarrow W_2 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	If $F_1 \rightarrow W_1 = 8$, then $F_1 \rightarrow W_3 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	Ave. value of $F_1 \rightarrow W_i \rightarrow S_i$
1	12	11	15	12
2	11	8	11	10
3	15	15	17	15
4	12	10	12	11
5	17	12	20	16

As per the result of introducing a direct route from factory 1 to sales outlets as a measure of making the supply chain network more resilient under 4 different disruption scenarios, the newest transportation cost compared to earlier scenarios and summarized in below table 6.

Table 6: Summarize of the resilience performance after introducing direct routes from factory 1 to sales outlets

Disruption Scenario	**Transportation cost under disruption**	**Resilience without new route**	**Transportation cost with new route**	**Resilience with new route**	**Impact on the resilience**
1	152,000	-0.15	145,600	-0.108	4.2% ↑
2	136,900	-0.041	130,000	0.011	5.2% ↑
3	140,300	-0.067	133,000	-0.012	5.5% ↑
4	151,000	-0.149	145,000	-0.103	4.6% ↑

As per the summarized resilience due to the new routes that has been introduced to the supply chain network, it is visible that overall, the resilience of the supply chain network has been improved.

2. Introducing direct routes from factory 2 to all sales outlets.

Table 7: Transportation cost from Factory 2 to Sales Outlets

Sales Outlet	If $F_1 \rightarrow W_1 = 6$, then $F_1 \rightarrow W_1 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	If $F_1 \rightarrow W_2 = 4$, then $F_1 \rightarrow W_2 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	If $F_1 \rightarrow W_1 = 9$, then $F_1 \rightarrow W_3 \rightarrow S_i = F_1 \rightarrow W_1 + W_1 \rightarrow S_i$	Ave. value of $F_1 \rightarrow W_i \rightarrow S_i$
1	11	10	16	11
2	10	7	12	9
3	14	14	18	15
4	11	9	13	11
5	16	11	21	16

After the new routes from factory 2 to sales outlets, the impact on the transportation cost and the resilience are presented in table 8.

Table 8: Summarize of the resilience performance after introducing direct routes from factory 2 to sales outlets

Disruption Scenario	Transportation cost under disruption	Resilience without new route	Transportation cost with new route	Resilience with new route	Impact on the resilience
1	152,000	-0.15	148,200	-0.127	2.3% ↑
2	136,900	-0.041	129,400	0.015	5.6% ↑
3	140,300	-0.067	138,400	-0.053	1.4% ↑
4	151,000	-0.149	147,000	-0.118	3.1 % ↑

As a result of the direct path from factory 2 to sales outlets the overall transportation cost has reduced compared to the transportation cost that occurred under disruption. Hence, the resilience of the supply chain network has improved. If we are to compare the different routes that was introduced, except for the disruption scenario 2, for all the other disruption instances, the resilience has improved more if there are direct routes from factory 1 to sales outlets.

4.1.6 Enhancing the capacity of Factories and Warehouses

Before deciding which factory, capacity or warehouses capacity should be increased, the capacity of usage of under different disruption scenarios along with the original optimized supply chain network was observed carefully as per the following table 9.

Table 9: Summarize of the capacity usage of factories and warehouses

Scenario	Usage of Factory 1 Capacity 10,000	Usage of Factory 2 Capacity 8,000	Usage of Warehouse 1 Capacity 2,500	Usage of Warehouse 2 Capacity 5,000	Usage of Warehouse 3 Capacity 7,000
Original	3,900	7,500	2,500	5,000	3,900
Disruption scenario 1	5,600	7,500	2,500	5,000	5,600
Disruption scenario 2	3,900	7,500	2,500	5,000	3,900
Disruption scenario 3	7,400	4,000	2,000	3,500	5,900
Disruption scenario 4	10,000	2,500	2,500	4,000	6,000

As per the table 9, it is observed that for most of the disruption scenarios, factory 2 capacity and warehouse 1 and 2 capacity are being fully used and even during the original state of the supply chain. Whenever the network is affected to its production or storage capacity, it seems to include the contribution from factory 1 and warehouse 3. Hence as a suggested solution, first it is assumed that instead of having a higher capacity for factory 1, to increase the factory 2 capacity by 40% and reduce the capacity of factory 1 by the same percentage.

Whereas, when it comes to the warehouse capacity rather than having the highest capacity with warehouse 3, to shift the 50% of its capacity to warehouse 1 and to measure its resilience. Due to the complexity in modifying the disruption scenario 4, except for that unexpected event for other 3 disruption scenarios the above-mentioned capacity changes have been adjusted and transportation and resilience was measured in below table 10.

Table 10: Summarize of resilience under change of capacities

Disruption Scenario	**Transportation cost under disruption**	**Resilience without new capacity changes**	**Transportation cost with new capacity changes**	**Resilience with new capacity changes**	**Impact on the resilience**
1	152,000	-0.15	145,200	-0.105	4.5% ↑
2	136,900	-0.041	137,300	-0.045	0.4 % ↓
3	140,300	-0.067	138,800	-0.056	1.1% ↑

According to the table 10, changes made to factory capacity and warehouse capacity has a positive impact on the resilience under disruption scenario 1 and 3. Whereas, under scenario 2, the transportation has increased by another 0.4% other than the initial increment.

4.1.7 Alternative transportation services

Before we decide any alternative transportation service to our entire supply chain network, here it is observed that common routes that has been presented in all the disruption scenarios and first to consider just those routes for a more cheaper transportation service.

Here it is identified that including the original network, under all the disruption scenarios, the routes that are from

1. factory 1 to warehouse 3
2. warehouse 2 to sales outlet 5
3. warehouse 3 to sales outlet 4

are being used. Hence starting from these routes would be the first to step to see whether it has any positive impact on the resilience supply chain optimization or not. Further it is assumed that it was possible to obtain more cost effective transportation method only for factory 1 to warehouse 3 for 7 units as the new transportation cost.

Table 11: Summarize of resilience under new transportation service

Disruption Scenario	**Transportation cost under disruption**	**Resilience without new options**	**Transportation cost with new options**	**Resilience with new options**	**Impact on the resilience**
1	152,000	-0.15	146,400	-0.114	3.6% ↑
2	136,900	-0.041	132,500	-0.008	3.3% ↑
3	140,300	-0.067	134,400	-0.022	4.5% ↑
4	151,000	-0.149	145,000	-0.103	4.6 % ↑

Finding more cost-effective transportation service helps to enhance the overall resilience of the network regardless of the disruption scenario that can affect the network. Here the most important fact that need to be emphasized would be rather than focusing on all the routes that are involved in the network, focusing on the one that is being used all the time. For instance, even though finding a more cost-effective transportation mode from factory 1 to warehouse 2 would not have a significant impact on the resilience consistently as the route is being used only under disruption scenario 4.

4.2 Results from Model II

4.2.1 Disruption Scenario 1

As per the figure 10, the demand increase in the outlet 2 has a greater impact on the total transportation cost compared to the demand increment in the outlet 1. If we see the trend line, the speed of increasing the transportation cost would be much higher than for the outlet 1.

Compared to the original network, the connectivity also has been increased by 2 under outlet 1 simulation and by 3 connections under outlet 2 demand simulation. The added routes compared to original, outlet 1 scenario, and outlet 2 scenario is as follows

- With respect to original and outlet 1; Factory 1 to Warehouse 1 was established, Warehouse 2 to Outlet 3 and Warehouse 3 to Outlet 3, are the added paths, and the route from warehouse 2 to outlet 4 was removed.
- With respect to original and outlet 2: Factory 1 to Warehouse 1 was established, Warehouse 3 to Outlet 2 and Warehouse 3 to Outlet 3, are the added paths.
- With respect outlet 1 scenario an outlet 2 scenario; Under the scenario 1, the route from warehouse 2 to outlet 3 is absent under outlet 2 simulation results. On the other hand, from warehouse 2 to outlet 4 and warehouse 3 to outlet 2 were added in outlet 2 demand simulation.

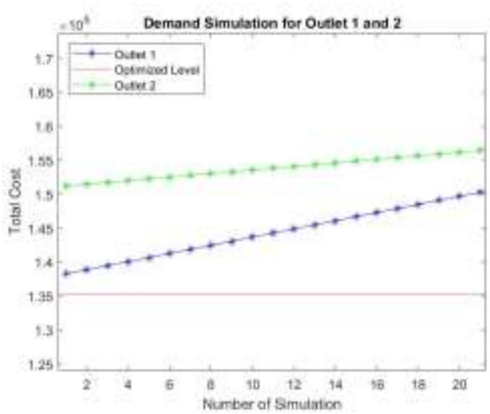


Figure 10: Demand Simulations

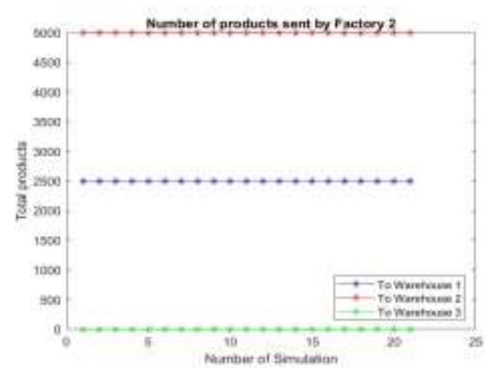


Figure 9: Factory 2 Product Distribution

Throughout the demand simulation for the outlet 1, it is observed in figure 9, that warehouses 2 and 3 are being fully used and the supply of goods for the warehouse has done by Factory 2, whereas the factory 3 capacity has not been fully utilized the at any time. While other warehouses are supplying products only for couple of outlets, the warehouse 2 has been supplying for 1, 2, 4 and 5 as it is shown in figure 11. And throughout the simulation, the number of products that has been supplied remained same. On the other hand, as it shown in the figure 12, the warehouse 1 supply to outlet 3 has been reduced and supplying for the outlet 1 has been increased.

Figure 11: Product Distribution by Warehouse 2

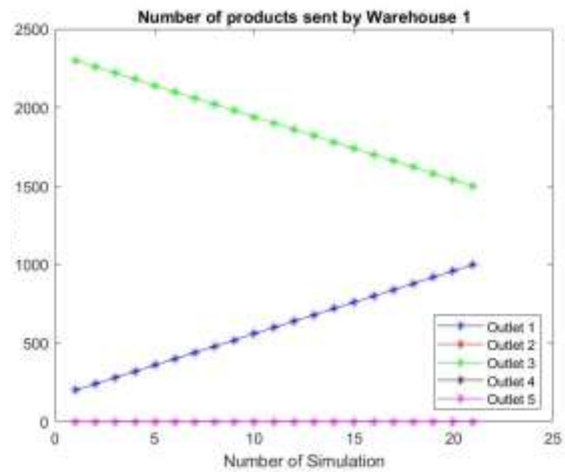


Figure 12:Product Distribution by Warehouse 1

The figure 13 and figure 14 represent the impact on the transportation cost when the respective penalty term is being considered which can be vary with the number of connections. The effect on connectivity on the network was also measure in that way, surprisingly the number of connections has been the same through entire simulation for outlet 1 which was 11 connections, whereas during the demand change in outlet 2, the number of connections was same for the entire time, which was 12 connections. Here the total transportation cost prior consideration of density of network was and after was presented. Since the number of connections was the same under n number of simulations, the cost reduction under the new objective function would be parallel to the old objective function under the disruption scenario 1.

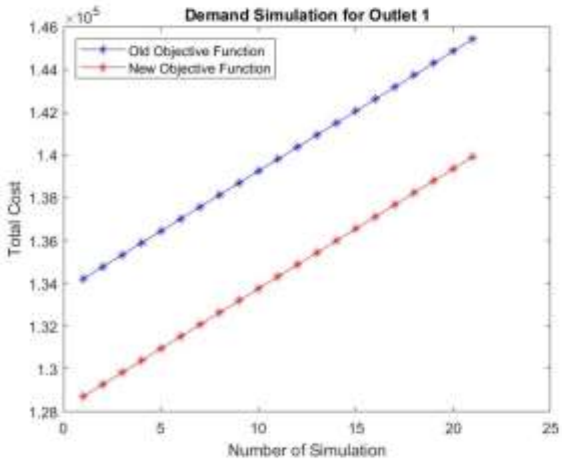


Figure 14: Before and After Considering the Density of the Network under Outlet 1 Demand Simulation

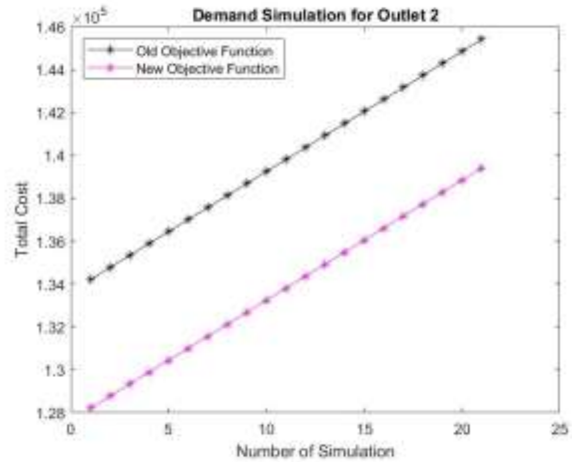


Figure 13: Before and After Considering the Density of the Network under Outlet 2 Demand Simulation

4.2.2 Disruption Scenario 2

According to the figure 15, due to the warehouse 2 capacity reduction simulation the total transportation cost is increasing rapidly. But due to the factory 2 capacity reduction, even though it causes to increase the transportation cost, it is not a consistent pattern, hence in order to make the system more resilient, there is possibility that we can resist the factory 2 capacity reduction in a case.

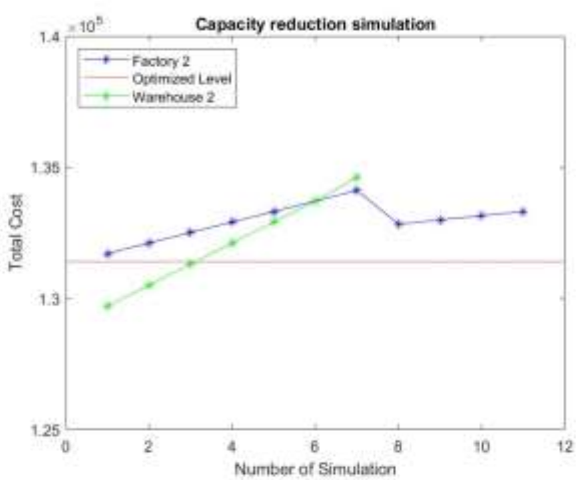


Figure 15:Impact of capacity reduction on total transportation cost

As per the figure 16 and 17, we can see that reduction in the capacity of factory 2 won't be making a significant difference on the products that are being sent by factory 1.

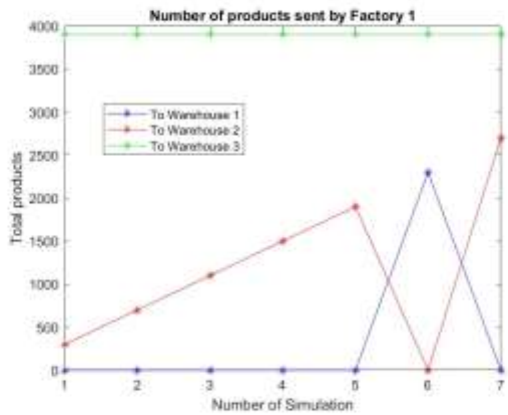


Figure 17: Impact of capacity reduction in Factory 2 on Goods distribution of Factory 1

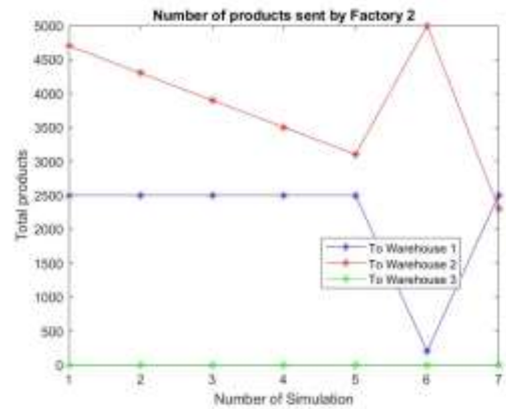


Figure 16: Impact of capacity reduction in Factory 2 on Goods distribution of Factory 2

Moving to the figure 18 and 19, which shows the warehouse 2's distribution of goods to different outlets under two scenarios, has not affected for the number of products that it's distributed to outlet 1 and 5. Till the end of the number of simulation, the warehouse 2 manages to continue supplying for outlet 2, whereas the reduction capacity in the warehouse 2 significantly reflect on the goods that are usually distributed to outlet 4 under warehouse 2 capacity reduction scenario..

Figure 18: Goods sent by Warehouse 2 to Outlets under Factory 2 capacity reduction

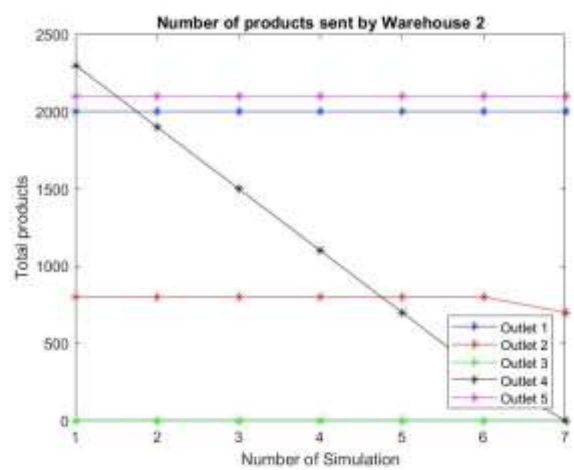


Figure 19: Goods sent by Warehouse 2 to Outlets under Warehouse 2 capacity reduction

When we focus on achieving the objective of the study while considering the density of the connections, throughout the simulation, the factory 1 remain using 10 connections, but this is still one connection greater than the original network connections. The added routes are,

• Factory 1 to warehouse 2

• Factory 2 to warehouse 2

Moving to the connectivity under warehouse 2 capacity reduction, till the last nth time the used number of connections was 10, but at the highest percentage of warehouse capacity reduction, the number of connections has reduced by 1. The overall impact on the transportation cost before and after considering the density of the connection under two sub disruptions scenarios with respect to supply are presented in figures 20 and 21.

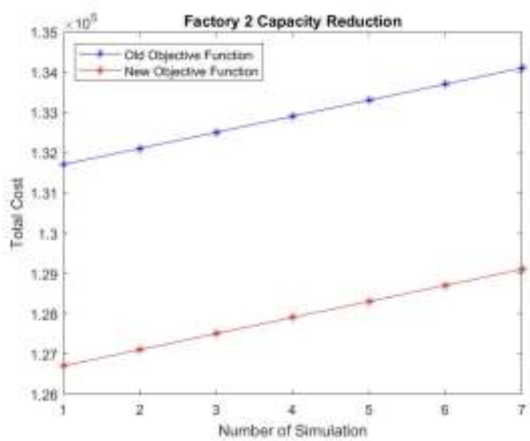


Figure 21: Before and After Considering the Density of the Network under Factory 2 Capacity reduction Simulation

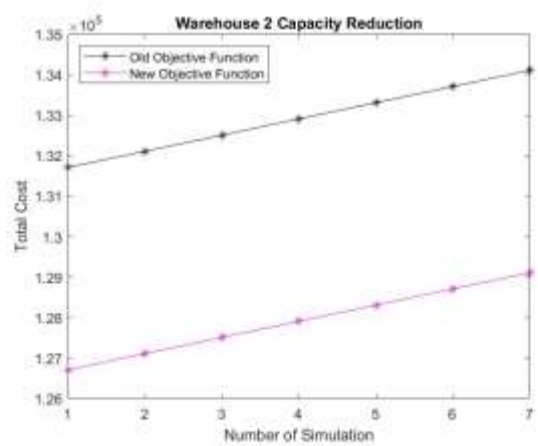


Figure 20: Before and After Considering the Density of the Network under Warehouse 2 Capacity reduction Simulation

Since the number of connections that has been used under both factory 2 capacity reduction and the warehouse 2 capacity reduction are the same, which is 10 the reduction in the transportation cost before and after considering the density of connections would be the same.

5 Summary and Conclusion

5.1 Summary and Conclusion drawn from the results

The objective of the thesis was to make a resilience supply chain optimization. The modeling of the study was done in two parts. The first part of the modeling was done with liner programming mathematical model with the objective of minimizing the transportation cost under different disruption scenarios and proposed measures were evaluated in terms of transportation cost to check whether the proposed methods make the supply chain network more resilient in terms of transportation cost. The suggested solutions can be considered as either long term strategic decisions or short term operational decision. And further can be applied to make the original supply chain network more resilient in the first place. Out of the 3 tested solutions, changes that made in capacity in plants and warehouses can be a long-term strategic decision and also the costliest decision. Once the plant's capacity was established it would be much more expensive to reduce the capacity or transfer its machinery to other plants which are much active in the supply chain network. Hence when we considering the changes that make in capacities, the decision makers should also consider the cost that involve in that process. As per the obtained results which present in the table 10, transferring a portion of the capacity of factory 1 to 2 and warehouses 3 to 1 has made the supply chain network more resiliently optimized. Hence this can be proposed as good solution that a company can consider if they are prioritizing to make their network more resilient.

Even it is much less costlier to distribute the goods straight away from the plants to sales outlets, due to the sudden demand shocks and issues in supplying the goods on time we cannot avoid using the warehouses entirely. But as the direct distribution of goods from its plants to sales outlets are making the SCN [1]more resilient as it given in the table 8, this proposed measure would be a one of the best solutions as it has positively affected the resilience of the SCN under all the disruption scenarios. Another long-term strategic decision that will align with this

[1] SCN: Supply Chain Network

resolution would be, during the first stage when the company decided to have their plant location and warehouse location, trying to have the plants much more center towards their highest demand area. This would require a thorough study of the market by expertise, but which would be worthwhile investment from the company point of view.

As the last projected solution, finding more cost-effective modes of distribution or transportation modes would be the best way to make the SCN more resilient optimized in terms of transportation cost. As per the values presented in the table 11, even finding a less costly transportation service even just for one route has the greatest positive impact in the resilience under all disruption scenarios. Here, having the priority on the routes are actively presented would give the company the advantage of having more resilient SCN with respect to their competitors. Along with the new technology, the global trends now the mode of transportation has plenty of options to choose from. Hence investing the time and money on finding such ways would have a positive impact on the overall supply chain network and its performance under disruption scenarios.

If we were to analyze the results under each disruption scenarios, under the first scenario where the SCN faced a volatility in demand, the resilience of the network has improved under each suggested solutions, where the improvement is 4.2% and 2.3% with introduction of new routes from factory 1 and factory 2 respectively, 4.5% under the changed that made in the capacities and 3.6% under alternative transportation services. Therefore, we can conclude that as a short-term solution, finding alternative routes would help the SCN to be resiliently optimized and if we were to decide which route to be implemented it is advisable to have the new path from the factory 1, while considering the other two solutions that are long-term changes that need to be modified with the network.

Whereas under the second disruption scenario, where there is breakdown in the original network, the immediate solution of finding alternative routes can cause the resilience to improve by 5.6% and 5.2% from the factory 1 and factory 2 respectively. Hence there are not much difference between the direct routes that has been suggested, under a give scenario like disruption 2, the company can go with either new route. Under the assumed breakdown routes in scenario 2, the capacity changes that suggested won’t be good impact on the network and its resilience as it tend to further reduce. But with the alternative distribution service, the resilience can improve by 3.3% compared to the resilience under disruption.

Moving towards the third disruption scenario, where the capacities of the factories and warehouses being affected negatively with respect to unchanged demand, distributing the goods through alternative routes has a good impact on the overall SCN, where it is 5.5% from factory 1 and 1.4% improvement in the resilience if the goods are transported directly from the factory 2 to sales outlets. As the hypothetical scenario suggests that the capacity has been reduced in factory 2, in that case having alternative routes from factory 2 to sales outlets would be futile decision to follow. Whereas, transferring the capacity from factory 1 to factory 2 would be also not a very good decision as it will improve only 1.1% of the resilience of the SCN. But as it works well in previous disruption scenarios, using alternative transportation modes has been affected positively 4.5% improvement in the resilience.

Under the last scenario that considered, where it was assumed the possibilities of happening demand volatility, break down in the routes, and reduction in capacities of plants and warehouses all together, the resilience of the SCN was enhanced by equal percentage of 4.6% through using alternative routes from factory 1 and using alternative transportation services. Hence the company has the freedom to whichever the method easier and cost-effective to optimize the network.

The second part of the modeling was focused on minimizing the transportation cost along with maximizing the connections within the network, using a mixed integer mathematical model. Here the additional binary variables were introduced to check the usage of a route. And a constant C was introduced to evaluate the final value of the penalty term that's been added to the new objective function. Further, under the second part of the modelling, two disruption scenarios with n times simulations were considered to evaluate how a variation of a disruption scenario can be affected to the network. And this evaluation is measured before and after considering the density of network. And it is identified that demand variation even in the 1st outlet has much more impact on the transportation cost and connectivity over the reduction in factory capacity or warehouse capacity. As the objective here is to study about minimizing the transportation cost with optimizing the routes, it helps the supply chain to become more cost efficient. Because the cost efficiency is a significance contribution to the profitability and sustainability which are major aspects of supply chain resilience.

Based on the study that was conducted the proposed research questions in chapter 1 was answered as follows.

1) Which disruption scenario has a major impact on the supply chain network in terms of transportation cost?

   It was identified that changes in the demand, mainly sudden rise in demand has the greatest impact on the transportation cost. And the size of the impact would almost same the impact that have when all the possibilities occurred at the same time. Hence it is advisable to project the demand thoroughly and make accurate predictions. Specially to focus on the seasonal trends, product launches so that the company can make preparation to make their SCN more optimized and more resilient.

2) What are the most suitable solutions to enhance the resilience of the supply chain network in each scenario?

   The most suitable solution would be to find alternative transportation services or distribution services. Apart from that having the possibility to use alternative routes has been suitable solution for all the considered disruption scenarios.

3) How can we make a resilient optimized supply chain network?

As it is shows in the results of the modelling part 2, through enhancing the density of the connections of the network, we can make more resilient optimized supply chain network. Plus this has been affected for the reduction in the overall transportation cost as well. Hence through focusing on more connected network would results in more resilient optimized model under disruptions while making the network more redundant. Therefore, the objective creating a more resilient optimized model under disruptions were achieved through this thesis.

4) Based on the results, what are the other factors that need to be considered in order to maintain a resilience supply chain optimization?

The plant and warehouse location plays a crucial role in maintaining a resilience supply chain optimization. Hence when the company first deciding the design of the network, this need to be carefully evaluated and possibly test runs should implemented. Making the supply chain network more flexible would be the key to an existing network to make more resilient.

As the established research questions were answered based on the study, the proposed objectives under the chapter 1 are achieved. As it is observed throughout the results, it is recommended that a company should be more open about maximizing the connectivity and to be more resourceful in terms of being able to access alternative distribution modes. As having a well-connected transportation network helps in redundancy of the network, it would ensure that that supply chain network would adapt to disruptions more smoothly. And here the dynamic route optimization mechanism would be help in terms of the response and recovery as it would help to be more flexible to make real time decisions and be proactive towards sudden evolving market.

Since the study was focused on dual objectives of minimizing transportation cost and maximizing the connectivity of the network, the thesis has added a new insight into the field of resilience in supply chain optimization with respect to transportation cost. As the study was based on hypothetical data, even though it can be considered as one of the limitations of the thesis, the studied models can be implemented with real data with the respective parameters and constraints, as in real life there can be much more constraints and variables that can be vary based on the line of the business. Since this area considered as more practical and more dynamic field, employing the model for more practical environment would open more possibilities to explore.

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