Evaluation of Critical Infrastructure Essential Businesses Amidst Covid -19 Using Network Optimization Models

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Abstract

This study evaluates the use of network optimization models in an essential infrastructure business during a pandemic. As per the Cyber Infrastructure Security Agency (CISA), there are 16 critical infrastructure sectors whose assets, systems, and networks, whether physical or virtual, are considered vital to the United States. Their incapacitation or destruction would have a debilitating effect on the security, national economic security, national public health or safety, or any combination thereof.

For this study, we primarily focus on the Healthcare and Public Health Sector (HPH). This branch is considered a core sector as it protects the economy from threats such as terrorism, infectious disease outbreaks, and natural disasters. This evaluation provides insights into the network optimization models used by a pharmaceutical company in administrating vaccinations to its local community during the COVID-19 pandemic. The intended result of the study is to provide an optimized delivery strategy by understanding the pros and cons of the network model that is being used currently and suggest a better strategical network model if available to administrate the vaccination program safely and efficiently throughout the United States.

Keywords: Critical Infrastructure Business, COVID-19, Network Optimization Models, Pharmaceutical Industries, Supply Chain.

1. INTRODUCTION

Coronaviruses are responsible for many common colds and are transmitted in a similar way to all viruses that infect the respiratory tract, primarily with droplets of saliva or mucus and infected hands. In December 2019, the city of Wuhan in Hubei Province (China's seventh-largest city and the 42nd biggest city in the world) became the center of a global epidemic of a new type of coronavirus, which has been officially known as severe acute respiratory syndrome (SARS) coronavirus 2 (SARS-CoV-2) or COVID-19 disease (Rothan et al.,2020). Coronavirus is the leading cause of death this year to date (05/30/2021) as per the worldometer data there have been 3,556,327 deaths and 171,010,454 active cases of the virus throughout the globe (Worldometer, 2021). However, the number of people infected with COVID-19 is higher than official statistics, as the vast majority who become infected have mild or no symptoms. Scientists are still trying to fully understand the virus and are constantly investigating the development of new vaccines and rapid diagnostics (Lamprou et al., 2020).

The World Health Organization (WHO), on 11 March 2020 announced the outbreak of COVID-19 as a pandemic. The COVID-19 pandemic is the worst after the Spanish flu pandemic in 1918 that infected one-third of the global population. Aassve et al. (2021). Scientists are still trying to fully understand the virus and are constantly investigating the development of new vaccines (Callaway et al., 2020) and rapid diagnostics (Sheridan et al., 2020). A recent report published in April 2020 has found that 94% of Fortune 1000 companies are experiencing disruptions because of COVID-19, while 75% have been negatively affected. (Supply Chain Digital, 2021). According to the report by the International Civil Aviation Organization (ICAO) in 2020 supply chain activities have been affected significantly due to COVID-19, there has been a steep decline in advancement of economy around the world. Emerging markets and developing economies went through a decline in growth over the last four financial quarters of 2020. Advanced economies have faced far more significant challenges even leading to foreclosure of businesses, (International Civil Organization, 2021), shows that the world's GDP has declined tremendously due to economic disruptions triggered by COVID-19. Indeed, the COVID-19 has affected many businesses around the world. From national lockdowns to closed borders, COVID-19 has disrupted economies and placed major strains on the supply chain and demonstrated how vulnerable the modern supply chain can be to disturbances (Zhu et al.,2020).

There have been numerous studies on network models and its positive affect on supply chain, but none of these studies come close to practicality. Craighead et al. (2007) explain the severity of disruptions in supply chain focusing on density, complexity, and node criticality. The paper explains the two main supply chain mitigation capabilities: recovery and warning but fails to provide an actual industrial scenario where disruption of supply chain has been prevented due to network models. (Gong et al., 2013). was able to explain the interdependence of network models to build a resilient supply chain network model.

In the example of 3J's trucking company (CIO insight, 2021) to restore the failure in their distribution system. The transportation team had to work around the clock to run effectively. However, the disruption of the telecommunication prevented the company to get vital information on road disruptions which caused failures in devising alternative routes. The telecommunication lines are a vital node for the trucking company, ignoring to restore them would have higher cost impact to the company both economically and with respect to time.

An examination of the supply chain literature points out the need for research on a resilient supply chain using network models. Sheffi et al. (2005). Authors such as (Snyder et al.,2006) address the disruption issue from the perspective of uncertainty of supply chain operations but none of these studies were able to capture a supply chain disruption from an in-process pandemic perspective.

This paper addresses the complexity in planning routes for delivery of Covid-19 vaccinations to pharmacies by looking at various network models while prioritizing the nodes which will help prevent disruption of the supply chain model. In this study we're primarily focusing on three supply chain models Scale Free, Random Network and Small World Network Models, these models will help us identify the critical nodes in the network, which will be used to harden the network to prevent any disruption in the delivery of Covid-19 vaccinations. The supply chain network is not only isolated to just critical nodes but also has dependency on the infrastructure and route planning. The data for this study is provided by a leading pharmaceutical company with over 10,000 stores in its network. The study is primarily focusing in one of the main districts of the organization with 60% of the stores at a Tier4 level ($800,000 Turnover Annually). The result from this study will help us build a framework for generating an efficient network model using a real-world scenario that will prevent disruption in the delivery of these emergency vaccinations.

2. THEORITICAL BACKGROUND

Network models are present all around us, whether it is the telephone lines that is used for audio communication, the running of appliances using residential electricity, or the mode of transportation used to get from one point to another, network models pervade daily life. Singh et al (2008). Network representation is present in so many diverse fields such as production planning, distribution, supply chain management, and resource management to name a few. During the blackout of 2003 (Electricity Consumers Resource Council, 2004) the loss of power supply caused the loss of production capacity of factories in the affected area. If the criticality of the node was identified in advance the factories could have made better decision concerning supply, inventory, and distribution. Supply chain design involves identification of configuration of network and the distribution of the resources over these networks. But how do major companies use these networks to maximize their profits? Different companies gave their own answers. Pfizer Inc (Gupta et al., 2002) modeled its distribution system as a two-echelon network which includes it two large distribution centers over its 35 third part pool distribution. Kellogg Company (Brown et al., 2001) developed an operation planning system to help determine where products are produced and how finished products and in-process products are shipped between plants and distribution centers, which reduced production, inventory, and distribution costs by an estimated $4.5 million in 1995. There are many companies using optimization techniques to design their supply chain, such as Deere's Commercial and Consumer Equipment (C&CE) Division's inventory management system (Troyer et al., 2005), and Hewlett-Packard's supply chain (Amaral et al., 2008). There have been recent advancements in dealing with complicated network models. Pan et al., (2013) did a study on network design for agile manufacturing with multiple echelons, multiple periods, and multiple customers with heavy demand. The problem was formulated to provide an integral solution to minimize the total operational cost. (Liu et. al., 2013) addressed the same issues by using a multi-objective mixed integer linear programming (MILP) model. The beauty of network models is that it allows for the visualization and conceptualization of the relationship between components of a system. These network models can be transformed into linear programming and can be solved using computers that use algorithms and software's to optimize the results (Hillier et al., 1997).

Critical Infrastructure: As per the Cyber and Infrastructure Security Agency (CISA) there are 16 critical infrastructure sectors (Figure 1) whose assets, systems, and networks whether physical or virtual are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety or any combination thereof. Brown et al. (2006). For this study, the concentration is on the Healthcare and Public Health sector (HPH) of the Critical Infrastructure Nodes. In the year 2003, the HPH sector was inducted into the critical infrastructure sector (Walker et al.,2018), since then this sector has been protecting all the other sectors of the economy from hazards such as terrorism, infectious disease outbreaks, and natural disasters (Department of Homeland Security., 2008). A basic understanding of the networks provides a big picture of how most critical infrastructure sectors can be modeled as networks. In a network, nodes and links abstractly represent the cities and roads, telephone switches and telephone lines, or an asset and its relationship with that asset. The most surprising property of most of the network is its high concentration of assets within a boundary. This creates a vulnerability to the network from manmade and natural calamities. Network theories help to model critical infrastructure as graphs to analyze appropriate frameworks in a practical way to model and harden potential targets in a critical network (Lewis et al., 2006).

FIGURE 1: Critical Infrastructures of United States.
Source: Department of Homeland Security (2008).

As there has been limited comprehensive study conducted on this topic, a great opportunity stands ahead, to survey the administration of vaccination during the pandemic at the store level. The study primarily focuses on 10 pharmaceutical stores within a given district in the state of Illinois. The advantages of conducting research on this topic will significantly help the country to administrate the vaccination in a safe manner by identifying the network and the critical nodes within that network to prevent an active or non-active threat situation.

Pharmaceutical stores around the United States started administrating COVID-19 vaccinations from the beginning of the year 2021(Center for Disease Control and Prevention, 2021). The mission of the National Center for Immunization and Respiratory Diseases (NCIRD) is the prevention of disease, disability, and death through immunization and by control of respiratory and related diseases, to successfully complete this mission it is necessary that every individual store gets the vaccines on time for the administration of this vaccination to the customers (NCIRD., 2021). With the surge in demand and not having a sufficient supply of vaccinations, the pharmaceutical companies started creating Hub stores in each of its districts. This helped the company to coordinate the supply chain of the vaccination at a macro level but at the same time increased the vulnerability to the stores in its district. A Hub store is an active pharmaceutical store that can store and distribute COVID-19 vaccinations throughout the district and administrate the vaccinations locally to its community. Everyday professionals with the license to carry bio-hazardous equipment and samples provide a shuttle service from the Hub store to deliver all the necessary vaccination doses, equipments and documentation to the stores within that district.

2. METHODOLOGY

The flow chart below (Figure 2) shows the visual representation of the steps involved in creating a network model.

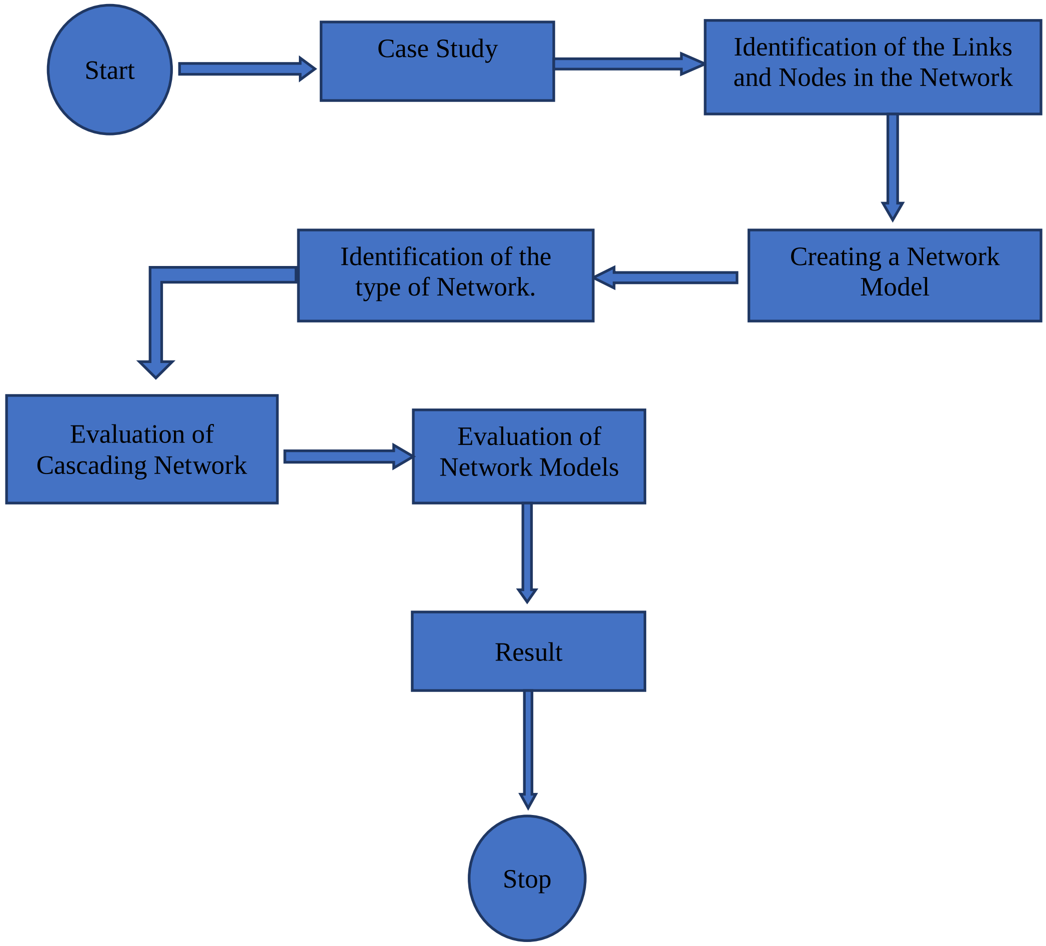

FIGURE 2: Methodology Flowchart.

This paper has been broken down to various tasks with respect to the case study. The study is being conducted in a district with 10 pharmaceuticals stores in the Midwest of United States of America that administrated Covid-19 vaccinations to the local community, The location of these stores has been masked in interest of the HIPAA privacy act. There is a primary store which shuttles Covid-19 vaccinations to all the stores within that district. The number of patients being vaccinated and enrolled for vaccinations were obtained from the organization and was classified into various nodes and links, each of the links represent the actual distance between each store in the network model. Zhan et al, (2017) conducted a similar type of study where they used the dynamic node vaccination methodology to prevent the contamination of nodes in a network. The topic of vaccination within a network has been well studied with a variety of models based on different approaches. Sometimes the global solution may not be obvious, (Cohen et al.,2003) or maybe difficult to obtain (Dushoff et al., 2007) Therefore, we have used the approach of concentrating within the 10 stores in the district to complete our study. Once we have a network model created, it is essential to identify the critical nodes in the network that will prevent disruption in the supply chain of these vaccinations. Since all the nodes cannot be hardened due to economical viability, it is important to check if the model can be prevented from a cascading failure. Once the network is secured, we will look at different network model paths to provide the most effective routing for the safe delivery of Covid-19 vaccinations to all the stores within that district.

3. CASE STUDY

The delivery of the Covid-19 vaccination to the stores has become a serious issue, with only a handful of locations within the district that offers vaccination for Covid-19, but with an unending demand of people willing to get vaccinated, presents unprecedented challenges to these stores. At the time of writing this paper each of the stores that administrated the vaccination were averaging 50 doses per day of vaccinations to the local community, yet it was difficult for the people to secure an appointment for the vaccination, with no sight of appointment availability soon. This had a rippling psychological effect like that of the toilet paper incident, where people started hoarding toilet papers as a fear of scarcity in the production of toilet paper spread fear and chaos around communities during the Covid-19 pandemic. A similar fear of delay in getting the vaccination has led to people disguising as senior citizens to get access to the vaccination, even stealing the vaccination and providing saline solutions in the form of vaccination in hospitals and pharmacies. The vulnerability to the stores is higher than ever before if these issues are not dealt with seriousness. It could result in cascading failures even jeopardizing the entire presidential operation of getting everyone vaccinated before the July 4^{th} deadline.

As it is essential for the transfer of the vaccination from the HUB store to all the other sites in the district, it is equally important to protect that specific node. If the HUB store gets affected by a human or natural cause it will have a cascading effect on the entire network as there would be disruption in the supply chain. One of the major challenges faced by the organization with delivery of the vaccination was route planning. Initially as there was only one stores within the district administrating vaccination it was easier to handle the storage and shuttling of the vaccinations. But as the number of stores started increasing, the complexity of delivering the vaccination increased. As per the CDC guidelines, if any store employee is exposed to the Covid-19 virus, the store is supposed to be closed for sanitization and the entire workforce is required to leave the store immediately to prevent further contamination. This meant that a shuttle on its route to deliver the vaccination to the store was risking the potency of the vaccination by travelling back to the hub store due to closure of the store. Other major concern with the delivery of the vaccination was the timely arrival of the vaccination to the stores. This was an issue at a store level as customers had to wait for hours for the vaccination to arrive and rescheduling of appointments was not an option. This led to people getting aggravated and even vandalizing the stores in the district. These were serious issues with respect to safety of the customers in the store. There is a need to identify the critical stores in the network and ensure an optimized route is followed to deliver the vaccination in a timely manner to these stores. The objective of this study is to provide solution to both these problems.

4.RESULT

4.1 Node & Link Identification

To identify each node and link in the network the correct location of each testing site needs to be known. Once the location is identified, google maps is used to pinpoint the location on an actual map. With the help of the map, all possible routes are created for the network. The network will represent all the potential links/arcs in the network. The following constraints have been created to chart the best routes for the delivery of vaccinations.

1. There are no toll roads taken into consideration while creating the routes
2. If two routes have the same distance, the fastest average route is taken as the primary route
3. A store can only have two other stores as a direct route.
4. There should be no isolated store (node) in the network.

Based on the constraints of the network, links that do not satisfy the constraints are removed from the network. Once all the non-feasible links are removed the actual distance between the nodes and the links are calculated.

As the location of each vaccination administrating site was shared by the organization, Google Maps was utilized to create a network model. (Figure 3).

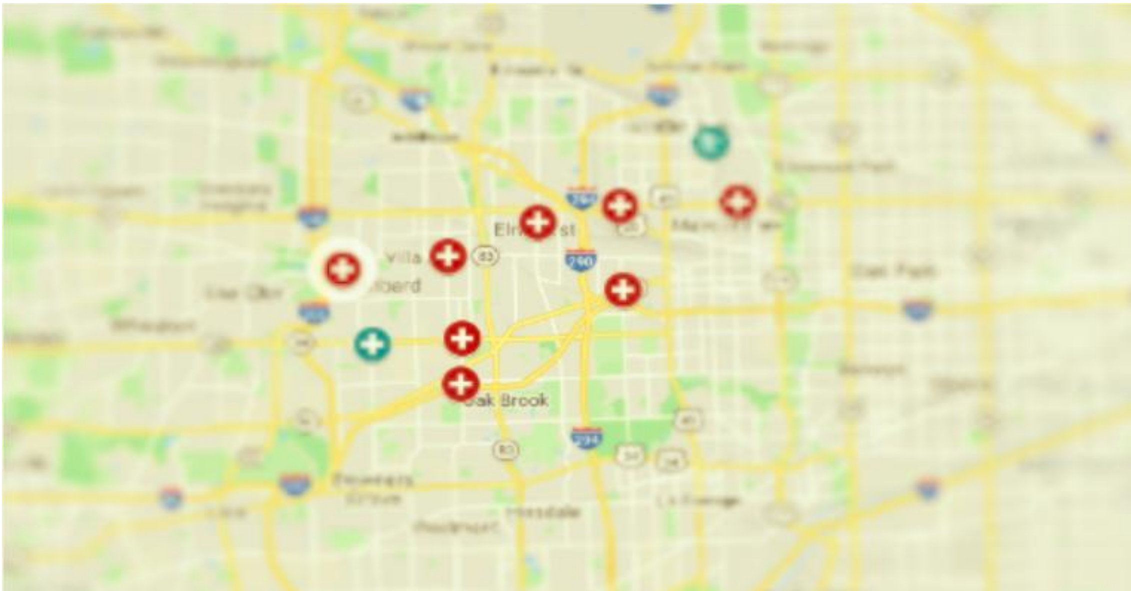

FIGURE 3: District Store Locations. Source: Google Maps.

4.2. Network Model

A network graph consists of nodes (vertices) and links(edges), nodes are the crucial points on any given network model and the links are the pathways that connect two or more nodes with each other. A path from node ‘A’ to node ‘B’ is a sequence of nodes and links that lead from ‘A’ to ‘B’. A graph is said to be complete when every possible edge is present. A complete graph can be either a sparse or a dense graph. A sparse graph is a graph with relatively fewer links than the number of nodes present, while a dense graph consists of the greatest number of edges present in the network. The nodes and links provide a network with the mapping function. Since the locations of the stores (nodes) were shared previously using the map shown above, the network graph was created by following the constraints of the model. All distance shown in the below figure (Figure 4) are actual distances between the stores in miles.

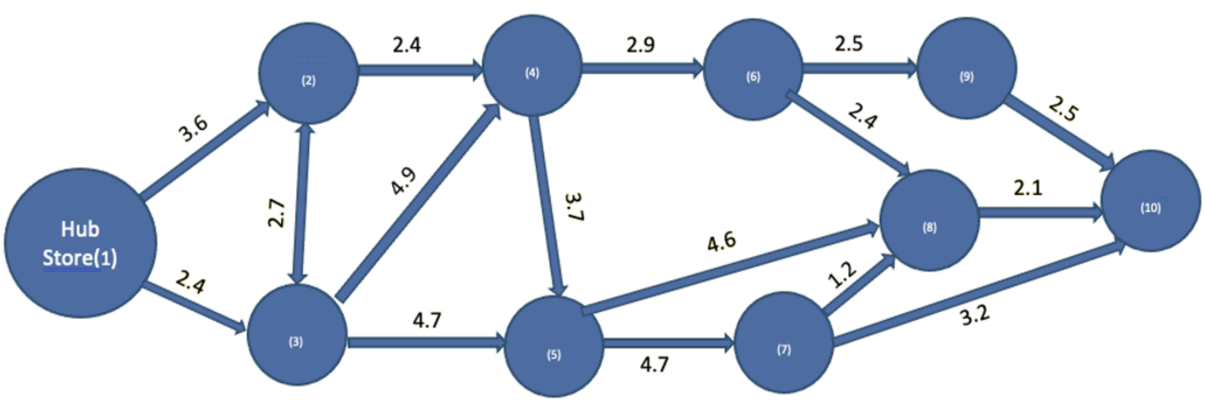

FIGURE 4: Network Graph for the District.

The network graph created is a sparse network as there are fewer than (N-1)/2 degrees in this graph. A degree in a graph is the number of links connected to that specific node. If a node has only one degree, the node is considered as terminal and if the degree of a node is zero then that node is called isolated as it does not connect to any other nodes in the graph.

4.3. Type of Network

This study concentrates on three classes of networks the Scale-free, small world, and Random network model. With the help of the network model, it is possible to conduct a critical node testing for the network which helps identify all the critical nodes in the network. If the critical nodes are identified, identification of whether the network is a cascading network or not, and how to avoid cascading failures within the network model needs to be understood. Once all the models have been applied to the network, an evaluation can determine the best model for this network.

4.4. Scale Free Network Model

A scale-free network test is a simple test used to identify whether a network is a scale free network model. The test counts the number of links that are attached to each node. Once the degree of each node is determined, these degrees are divided by the number of nodes in the network. This gives the frequency of nodes for the number of links. The node's frequency is plotted as a histogram to the number of links. If the resulting histogram has a curved shape, with a rate of decline of $(1/k)^{p}$ where P is greater than 1 then the network is considered a Scale Free Network (Albert et al., 2009)

Degree	Frequency	Power Law	Node Count
1	0%	47%	0
2	20%	30%	2
3	40%	22%	4
4	40%	22%	4
5	0%	14%	0

TABLE 1: Scale-Free Test Table.

With the help of Table 1, a plot of the histogram graph for frequency versus links was constructed.

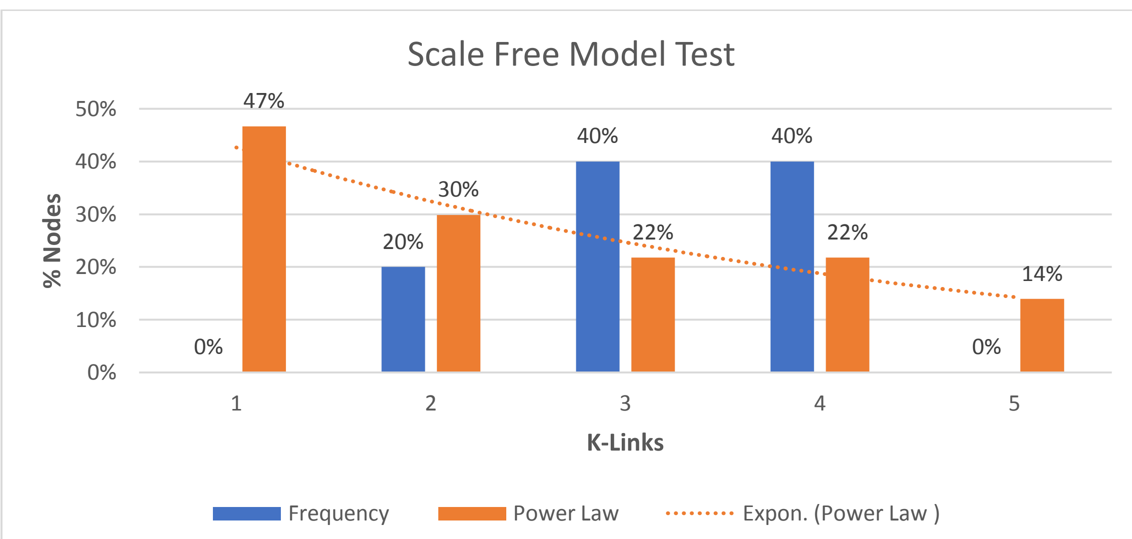

FIGURE 5: Scale-Free Test Graph.

From the graph, the following conclusions can be deduced.

1. The frequency of nodes increases with increase in the number of links
2. The most common nodes have 3 or 4 links
3. As our network does not decrease with an increase in the number of links this network cannot be classified as a Scale-Free Network.

4.5. Small World Network

As the network, created is a sparse network it satisfies one of the characteristics of a small-world network. There is a need to test the network for the remaining characteristics to check if the network is considered a small-world network.

As per Duncan Watts conditions for a small-world network are as mentioned below:(Duncan et al., 1999).

1. The network should be large
2. The network should be sparse
3. The network is decentralized
4. The network is highly clustered
5. The network is connected to every other node in the network.

For this study, the network is relatively large and sparse which satisfies the first two conditions of the small-world network. However, the network graph is not decentralized as the root node is present at the end of the network model. The network does not have a cluster formation as there are no nodes in the network that connect to every other node with the minimum number of hops. As this network does not have all the above-mentioned characteristics the network cannot be classified as a small-world network.

As the network does not fall into any of the above two mentioned classifications, it can be considered that the network is to be part of a random network model. In a random network model, the critical nodes are picked based on priorities.

4.6. Cascading Networks

Cascading failures are like epidemic when it comes to critical infrastructure models. Considering our model to be a cascade network and Covid-19 being the reason behind fault in our networks we can use this model to understand cascading failures. Let λ be the probability of the virus spreading along the links. This means that we are considering a closure of a vaccination site only due to employees being affected by the virus or a natural cause. Let χ be the store coming back to its normal function also called as the cure rate and ϖ be the stores that are dysfunctional also called as the infection rate. In a random network model cascading failure can be prevented if the spread rate (λ) which is the ratio of infection rate (ϖ) to the cure rate (χ) is less than the epidemic threshold **(**λ_c) of the network. In an ideal mathematical world if the spread rate is above 1 the fault will persist and continue to spread and if it is less than 1 it eventually fades away. But this is not true in the real world, there is another parameter which plays a significant role called the epidemic threshold λ_c **t**hat determines if the fault persists or dies out after a certain length of time.

$$\lambda = \varpi / \chi \qquad \textbf{(7.1)}$$

From the above mathematical model, we can conclude that in a random cascade network, the epidemic will die out if the spread rate is less that the epidemic threshold, otherwise all the nodes will have a cascading failure. Therefore, it is important that the Hub store is protected such that λ_c is greater than or equal to λ, which will help us prevent the disruption in timely delivery of the vaccination.

4.7. Evaluation of Network Model

The network graph analysis gave the information regarding the type of network and the critical nodes in the network that could prevent a cascading failure in the network. To prevent the disruption in the supply chain of the vaccination, we can use the same network model to map out an optimized route. The following constraints helped the formation of the optimized network model.

1. The HUB node is the starting point of the network.
2. The optimized path should go through all the nodes only once

After determining the distance between each node and establishing the constraints for the network, different network optimization models are used to find the best possible route for this network.

4.8. Shortest Path Model

This model helps to achieve the shortest distance from the root node to the last node in the network. To find the shortest route excel was used to optimize the route using analytical solver. The first step is to create a table that showcases the distance of each node that has been linked to all the other nodes in the network (Table 2). In the next column, an on-route tab was created, this tab is the variable column that makes known if the path would pass through a specific node or not. If the on-route value is 1 then the path moves through that respective node otherwise it would be 0. Initially when added to this column, leaving all the on-route values to be blank. Now adding the constraint to this model, the SUMIF function is used (Table 3), here the function will look for the supply/demand of 1 unit from the root node to the final node. The net flow generated is the difference between the flow out to that of flow in, resulting in a net flow of 1 at the origin and -1 at the last node. The objective cell is the sum product of the on-route column with the distance column giving the total distance in miles for the chosen path (Table 4).

	B	C	D	E	F	G	H	I	J
3	From	To	Distance	On Route		Nodes	Net Flow		Supply/Demand
4	1	2	3.6	1		1	1	=	1
5	1	3	2.4	0		2	0	=	0
6	2	3	2.7	0		3	0	=	0
7	2	4	2.4	1		4	0	=	0
8	3	2	2.7	0		5	0	=	0
9	3	4	4.9	0		6	0	=	0
10	3	5	4.7	0		7	0	=	0
11	4	2	2.4	0		8	0	=	0
12	4	3	4.9	0		9	0	=	0
13	4	5	3.7	0		10	-1	=	-1
14	4	6	2.9	1					
15	5	3	4.7	0					
16	5	4	3.7	0					
17	5	7	4.7	0		*Total Distance*	13.4		
18	5	8	4.6	0					
19	6	4	2.9	0					
20	6	8	2.4	1					
21	6	9	2.5	0					
22	7	5	4.7	0					
23	7	8	1.2	0					
24	7	10	3.2	0					
25	8	5	4.6	0					
26	8	6	2.4	0					
27	8	7	1.2	0					
28	8	10	2.1	1					
29	9	6	2.5	0					
30	9	10	2.5	0					
31	10	7	3.2	0					
32	10	9	2.5	0					

TABLE 2: Potential Links for Shortest Path Model.

	H
3	NetFlow
4	SUMIF($B$4:$B$32,G4,$E$4:$E$32)-SUMIF($C$4:$C$32,G4,$E$4:$E$32)
5	SUMIF($B$5:$B$32,G5,$E$5:$E$32)-SUMIF($C$5:$C$32,G5,$E$5:$E$32)
6	SUMIF($B$6:$B$32,G6,$E$6:$E$32)-SUMIF($C$6:$C$32,G6,$E$6:$E$32)
7	SUMIF($B$7:$B$32,G7,$E$7:$E$32)-SUMIF($C$7:$C$32,G7,$E$7:$E$32)
8	SUMIF($B$8:$B$32,G8,$E$8:$E$32)-SUMIF($C$8:$C$32,G8,$E$8:$E$32)
9	SUMIF($B$9:$B$32,G9,$E$9:$E$32)-SUMIF($C$9:$C$32,G9,$E$9:$E$32)
10	SUMIF($B$10:$B$32,G10,$E$10:$E$32)-SUMIF($C$10:$C$32,G10,$E$10:$E$32)
11	SUMIF($B$11:$B$32,G11,$E$11:$E$32)-SUMIF($C$11:$C$32,G11,$E$11:$E$32)
12	SUMIF($B$12:$B$32,G12,$E$12:$E$32)-SUMIF($C$12:$C$32,G12,$E$12:$E$32)
13	SUMIF($B$13:$B$32,G13,$E$13:$E$32)-SUMIF($C$13:$C$32,G13,$E$13:$E$32)
14	SUMIF($B$14:$B$32,G14,$E$14:$E$32)-SUMIF($C$14:$C$32,G14,$E$14:$E$32)

TABLE 3: SUMIF formula to calculate the NetFlow.

	G	H
17	Total Distance	SUMPRODUCT(D4:D32,E4:E32)

TABLE 4: SUMPRODUCT formula to calculate the Total Distance.

Once all the data is updated on excel, the analytical solver function to optimize the data helped find the shortest path. The Solver parameters would be to set the objective cell to "Total Distance", by changing the variable cells "On Route" which are subjected to a constraint of "NetFlow" being equal to the "Supply/Demand". The variables would be non-negative, and the solving method is simplex LP (Figure 6). Once the optimized result is obtained, the shortest path is represented by highlighting the links of the path on the network graph. (Figure 8) The shortest route has a total distance of 13.4 miles.

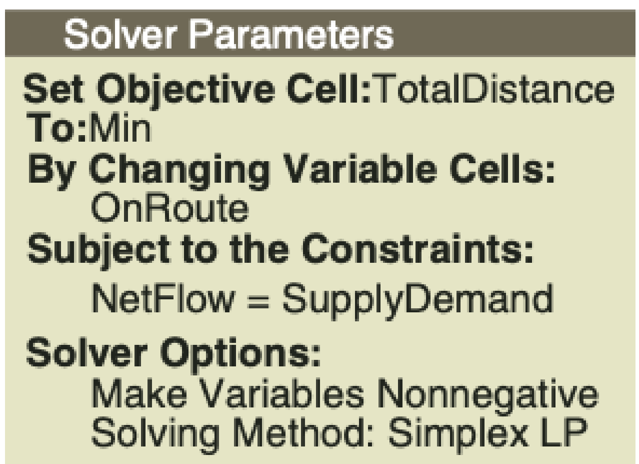

FIGURE 6: Solver Parameters for Shortest Path.

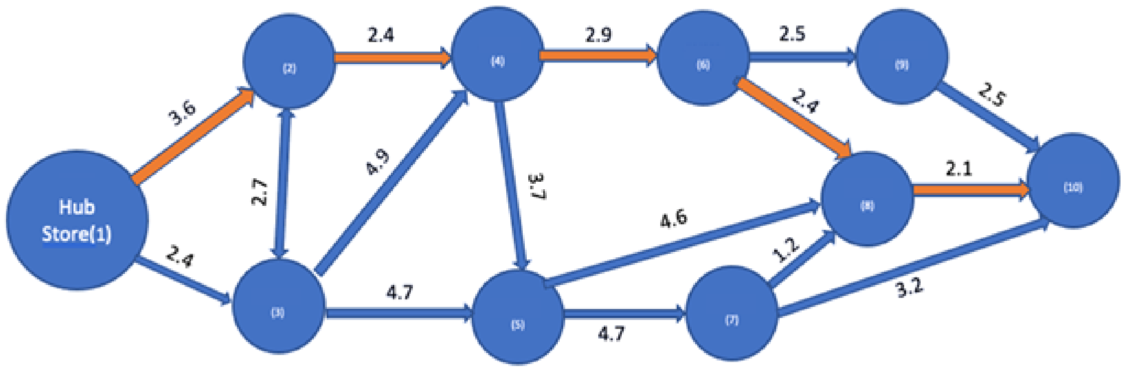

FIGURE 7: Shortest Path Model.

The route provides the least distance to reach the last store in the network but has failed to connect all the nodes in the network. Thus, this model does not fit the constraint model.

4.9. Minimum Spanning Tree Model

This model is very similar to the shortest path model; in both the model an undirected and connected network is utilized. In a minimum spanning tree model, the required property is that the chosen path should provide a path between each pair of nodes. With the potential links between each node, it is possible to design the network by having the minimum number of links that have a path between every pair of nodes. If there are N nodes present in a network, there should be only N-1 links present in the network to satisfy the model's condition. This model is easy to be put into practice as this is one of the few models where being greedy at every iteration can still give an optimal solution for the network. The process is simple, identify a node where the path is desired to begin from. In this case, it is the Hub Store. Once identified connect this node to the nearest distinct node. Once connected, identify the closest unconnected node to this distinct node. Connect these two nodes and repeat the iteration until all nodes (N) relate to (N-1) links. Table 8.4 shows all the potential paths for the network and the highlighted columns show the minimum spanning tree links for the network.

From	To	Distance	On Route
1	2	3.6	🔴
1	3	2.4	🟢
2	3	2.7	🟢
2	4	2.4	🟢
3	4	4.9	🔴
3	5	4.7	🔴
4	5	3.7	🟢
4	6	2.9	🟢
5	7	4.7	🔴
5	8	4.6	🔴
6	8	2.4	🟢
6	9	2.5	🟢
7	8	1.2	🟢
7	10	3.2	🔴
8	10	2.1	🟢
9	10	2.5	🔴
	Total Distance	22.3	

TABLE 4: Potential Links for Minimum Spanning Tree Model.

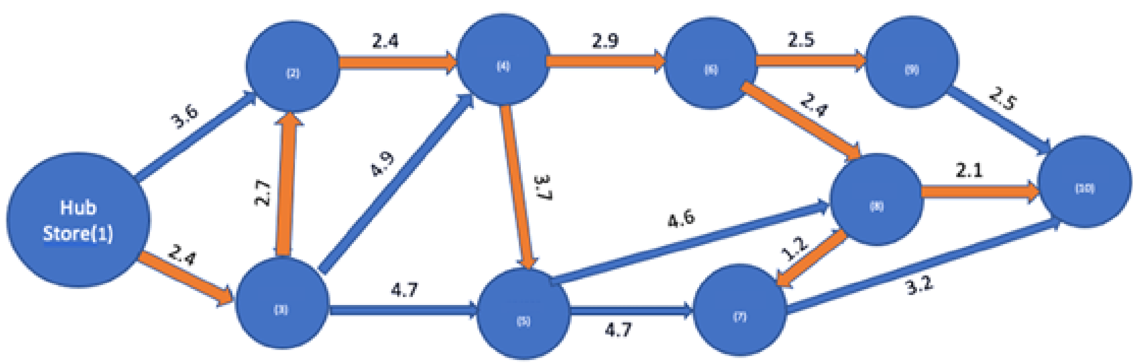

FIGURE 8: Minimum Spanning Tree Model.

The minimum spanning tree model gives a total distance of 22.3 miles for the network. The highlighted path in the figure shows the critical path for the network. This model connects all the nodes of the network and ensures reaching the last node of the network but takes a longer distance to cover all the nodes. This model would have been effective if only trying to establish a critical network path. As the path is not continuous the shuttle can revisit a node within the network more than once which means it would involve more distance and operation cost than what has been estimated above.

4.10. Traveling Salesman Model

There are close parallels to a minimum spanning tree and a traveling salesman problem (TSP). Each of these models is presented with all the potential links in the network and in both the models, the links need to be chosen to create an optimal path. The objective of the model to minimize the total distance traveled. For a traveling salesman problem, it is needed to find the distance of every single node to every other node in the network. Table 8.5 represents the distance matrix for each node in this network. The objective here is to make sure that start begins from the HUB node and returns to the HUB node by covering all the other nodes at the end of the iteration. Once the matrix is created, nodes are arranged as a random sequence in excel. Now to find the distance between each node in the sequence this has been arranged using the index function. Once the distance between each node is found according to the sequence, summation of all the distances and that will give the total distance of the network for a random sequence. To find the best sequence optimization of the model is determined using the excel solver. (Figure 9) The set objective is to minimize the total distance of the sequence by varying the random sequence that have been created for the network. As the shuttle service is needed to visit every node only once, constraining the sequence model to be different after each iteration was completed. The solving method being used would be the evolutionary method rather than the simplex LP model. As the total distance for a random sequence model the evolutionary model will try to find a better solution than the existing solution. Once the model finds an optimized solution closer to the initial solution it will try to find a better solution than the second optimized solution to figure out the best-optimized solution after several iterations.

Store No.	HUB	2	3	4	5	6	7	8	9	10
HUB	-	3.6	2.4	5.7	5.2	8.6	9.9	10.2	11.1	12.2
2	3.6	-	2.7	2.2	4.7	5.2	8	7	7.6	9.1
3	2.4	2.7	-	4.9	4.7	7.8	9.4	9.7	10.2	11.7
4	5.7	2.2	4.9	-	3.6	2.9	5.3	4.7	5.4	6.7
5	5.2	4.7	4.7	3.6	-	4.8	4.7	4.6	7.3	6.7
6	8.6	5.2	7.8	2.9	4.8	-	4.5	2.3	2.5	3.9
7	9.9	8	9.4	5.3	4.7	4.5	-	1.2	5.5	3.2
8	10.2	7	9.7	4.7	4.6	2.3	1.2	-	4.4	2.1
9	11.1	7.6	10.2	5.4	7.3	2.5	5.5	4.4.	-	2.5
10	12.2	9.1	11.7	6.7	6.7	3.9	3.2	2.1	2.5	-

TABLE 5: Distance Matrix .

Solver Parameters

Set Objective Cell: Total Distance

To: Min

By Changing Variable Cell:
Sequence

Subject to the Constraints:
Sequence = Diff

Solver Options:
Make variables Nonnegative
Solving Method: Evolutionary

FIGURE 9: Solver Parameters for Travelling Salesman Model.

Sequence	1	2	4	6	7	10	9	8	5	3	1
Distance	3.6	2.2	2.9	4.5	3.2	2.5	4.4	4.6	4.7	2.4	
Total Distance	30.6										

TABLE 6: Optimized Travelling Salesman Model.

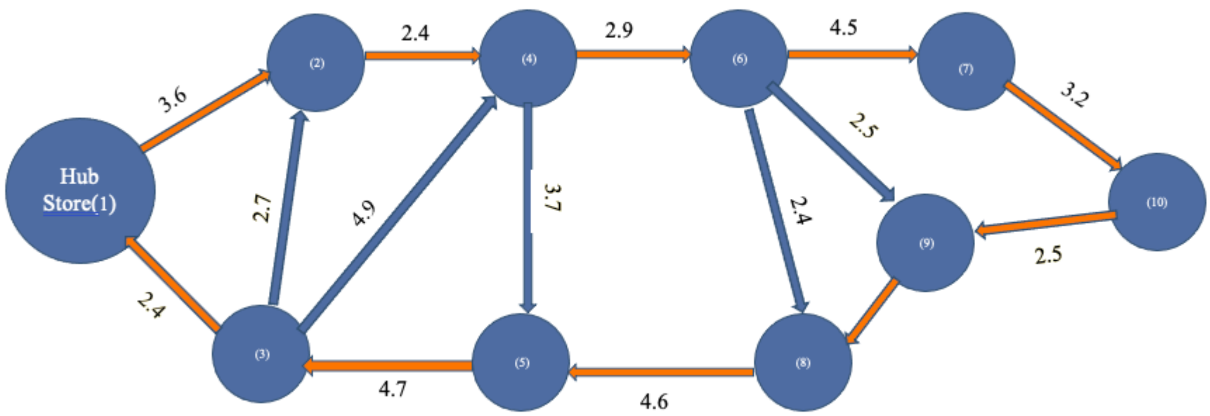

FIGURE 10: Traveling Salesman Model.

The Travelling salesman model gives a total distance of 30.6 miles for the network. The highlighted path shows the best optimal route for the transportation of the vaccination. This model gave us the shortest distance, that adhered to all the constraints of the model. The travelling salesman model will ensure that the delivery of the vaccination will not get disrupted to any of the stores as it follows a cyclic route and ensures all the nodes in the district are covered in a single routing plan. Even if a single store is affected by any kind of disruption the vaccination shuttle can continue its route to the next store and deliver the excess vaccination to that store. This can ensure that the people effected with the closure of the store can still go to the nearest store from the affected area and can still get vaccinated which can help prevent a chaotic environment in the community. This model is not only efficient in preventing disruption of the supply chain but is also economically viable to the organization. The model has the least complication involved with route planning and has the shortest distance with respect to a time constrained model.

5. CONCLUSION

The framework presented in this paper takes into consideration the disruption of the supply chain by considering the interdependency between the supply chain network model and the infrastructure of the organization. If any of the nodes apart from the root node fails in this network the failure would be considered as a non-cascading failure. The node that fails in the network will have a very small impact on the overall network. To prevent this kind of failure it is important to harden all the nodes and links in the network which would be expensive. If the root node (HUB) is infected or destroyed in this model then the resulting failure would be a cascading failure, as the failure of this single node can have a larger impact on the entire network. This would be the worst-case scenario as cascading networks would destroy the entire network system and prevention of a cascading failure would be expensive. The goal of this study was to provide an efficient resilient strategy for real life situations. Zhan et. Al (2017) methodology was just a simulation of a real-world problem using computational algorithms, it failed to take into consideration the human element which is considered as a major limitation. Similarly, Gupta et al. (2002) and Brown et al, (2001) study was focused on the supply chain aspect from the supplier plant to the distribution centers but failed to emphasize the need to strengthen the nodes closer to the end consumer, to prevent any kind of disruption in the supply chain network. The travelling salesman model fits this strategy by ensuring all the objectives of the network is accomplished. The use of the optimal route can also reduce the operation cost and reduce the vulnerability faced during these unprecedented times. This is a first of a kind of a study conducted for this organization. However, there exists some limitation to our research, which are also a direction for future research.

During the research study there were a few limitations to the study that were identified. As the study was confined to only one of the districts of the pharmaceutical store, the study was not able to identify the potentials of working with other districts within the area. The company having nearly 10,000 stores nationwide it was difficult to obtain the data for each district and conduct the analysis. Therefore, the critical nodes in an event of a cascading failure can be supported from Hubs that are present within the same area but different districts. This limitation was identified however was not pursued due to time constraint and the lack of data for the entire organization. These limitations can be considered for future research and can be used to help understand the models used in this study from an organization perspective to implement the analysis of the work done during the research. With Covid -19 vaccinations being a major priority across the United States and with no affordable strategy for the protection of the stores throughout the country this study acts as a building block, emphasizing the necessity of identifying critical nodes within a network. The cost involved in hardening or protecting all the stores in the district is not practical, therefore we identified the critical nodes in the network. Protection of these specific stores is the most practical solution to the problem.

As per this study, classification of the network as a random network was determined. But random networks have a lot of limitations concerning critical infrastructure. This study should be used as a foundation to convert the network into a structured network (scale-free, small world, Pareto, etc.). Where protection of a few critical nodes could minimize the cascading effects on the network, it could help to ensure the safety and well-being of the surrounding community. According to an experimental study, a random network whose nodes get randomly infected has a 99% chance of failure on average whereas a scale-free network with a protected hub has only 66% chances of average failure. The survivability rate of the scale-free network is much more optimal when compared to that of the random network. The efficacy of a critical node analysis has still not been proved, as their application to real-world situations is limited. This case study in the middle of the pandemic year will act as a research analysis tool to prove the importance of the analysis of the critical nodes in a network model for essential service organizations.

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