RISK ANALYSIS AND MANAGEMENT OF

NEW JERSEY FOOD SUPPLY CHAIN

By

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ABSTRACT OF THE THESIS

RISK ANALYSIS AND MANAGEMENT OF

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New Jersey is known as the Garden State for its dynamic, thriving food production industry that runs the gamut from vegetable growing to sophisticated manufacturing operations. Today New Jersey has a thriving $126 billion food industry and agriculture sector that grows every day. With such a vast and complex system, the food supply chain in New Jersey is vulnerable because a single disruption to one element could spread out and bring huge impact to the entire system. Such a ripple effect may have a tremendous impact on not only the state's economy and job market, but also the state's security, vulnerability, and resiliency. Food supply chain risks may occur naturally, intentionally, or accidentally. No matter how a risk originates, it may propagate along the connected members and then impact the entire network. Hence, it is critical to identify the risks in the New Jersey food supply chain and analyze their impacts. Understanding how risks propagate through the network will provide us with important insights into vulnerability assessment for the critical assets in the New Jersey food supply chain. Risks can then be better controlled, mitigated, and prepared for.

This thesis first introduces the current status of the New Jersey food supply chain and then reviews the existing studies on supply chain risk modeling and propagation. To identify the critical assets in the New Jersey food supply chain and their relationship, the important nodes, links, risks, and failure probabilities are analyzed. The New Jersey food supply chain is then configured with 293 nodes. A new model for risk propagation is developed based on the traditional virus propagation models. The proposed model is then implemented in simulation for the New Jersey food supply chain network. Simulation results demonstrate how risks propagate through the network and which assets are the most critical ones in the New Jersey food supply chain. Future efforts will be devoted to more simulation analysis and improving the risk propagation model.

ACKNOWLEDGMENTS

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CHAPTER 1

Introduction

New Jersey (NJ) is known as the Garden State for its dynamic, thriving food production industry that runs the gamut from vegetable growing to sophisticated manufacturing operations. Home to some of the world's leading food companies, New Jersey has a long, rich history in the food industry. Strategically located in the heart of the Northeast corridor, New Jersey provides easy access to one of the most affluent consumer markets in the world. A distribution center in central New Jersey can serve more than 22 million consumers who collectively have nearly $800 billion in disposable income and live within a two-hour drive. The Port of New York and New Jersey, the third busiest port in North America and the largest on the East Coast, makes it easy to import and export food products. According to the United States Census Bureau's 2012 release, New Jersey is home to more than 50,000 food manufacturing companies, R&D facilities, distribution centers, retailers, and farms – employing more than 440,000 people [1]. Today New Jersey has a thriving $126 billion food industry and agriculture sector that grows every day. With such a vast and complex system, the food supply chain in New Jersey has a tremendous impact on not only the state's economy and job market, but also the state's security, vulnerability, and resiliency.

However, the New Jersey food supply chain is vulnerable because the network is so vast and complex that a single disruption to one player would spread out and make huge impact on the entire network. Such a ripple effect [2] may also threaten the state's economy and politics. A disruption to food supply chain may be caused by internal risks, external risks, or natural disasters.

No matter how risks originate, they would propagate along the connected members and then impact the entire network. For example, when some serious machine failures occur in a food processing plant, the manufacturer may not be able to meet its planned throughput. Due to the shortage in finished goods, the manufacturer may not get enough payment from retailers to buy raw materials from suppliers. So, it would bring financial risks to the vendors, who have no money to support their business and may go into bankruptcy. In this way, a single risk would expand explosively to the whole network and may eventually go beyond control. For example, due to a severe flood, the output of agricultural products may be severely reduced and the food supply may not meet the demand. This is a direct impact. Meanwhile, due to shortage in supplies and possible damages to major transportation, food processing may not be able to continue. As the manufacturer could not get payments from retailers, financial risks and management risks would emerge and might result in labor strike or other societal issues. These indirect risks could spread out to the entire supply chain network and even destroy the industry.

Hence, it is critical to identify the risks in the New Jersey food supply chain and analyze their impacts. It is also of great importance to assess the vulnerability of the critical assets in New Jersey food supply chain, so that risk mitigation and preparation strategies can be better developed.

1.1 Background

A food supply chain refers to the processes that describe how food from a farm ends up on our tables [3]. The processes include production, processing, distribution, consumption and disposal. The food reaches us via food supply chains through which food moves systematically from producers to consumers while the money consumers pay for the food goes to people who work at various stages along the food supply chain in the reverse direction. Every step of the supply chain requires human and/or natural resources. A food supply chain network is a complex structured map that describes the food flow and associated members from farms to the end customers. Figure 1.1 is an illustration of a food supply chain network. The four essential components that are responsible for moving the goods from the beginning to the consumers – farms, marketers, food processors, and wholesalers/ distributors – are shown in blue. First, raw materials such as crops are cultivated and harvested by farms and then moved to marketers, waiting for further processing at food manufacturer plants. After food processing, finished goods are shipped to distribution centers who will distribute the goods to final destinations: retailers who will arrange further sales at local supermarkets, caterers who will turn food into dishes at restaurants, and consumers who will buy them directly. In New Jersey, imports and exports are also involved in the network, since the Port of New York and New Jersey is the largest port on the East Coast, making it easy to import and export food products.

New Jersey's strategic location and strong transportation infrastructure provide an easy access to one of the most affluent consumer markets in the world. Hence, the food items produced in New Jersey not only need to meet the local demands, but also need to serve other states. Meanwhile, the goods imported from other places are also distributed to in-state consumers.

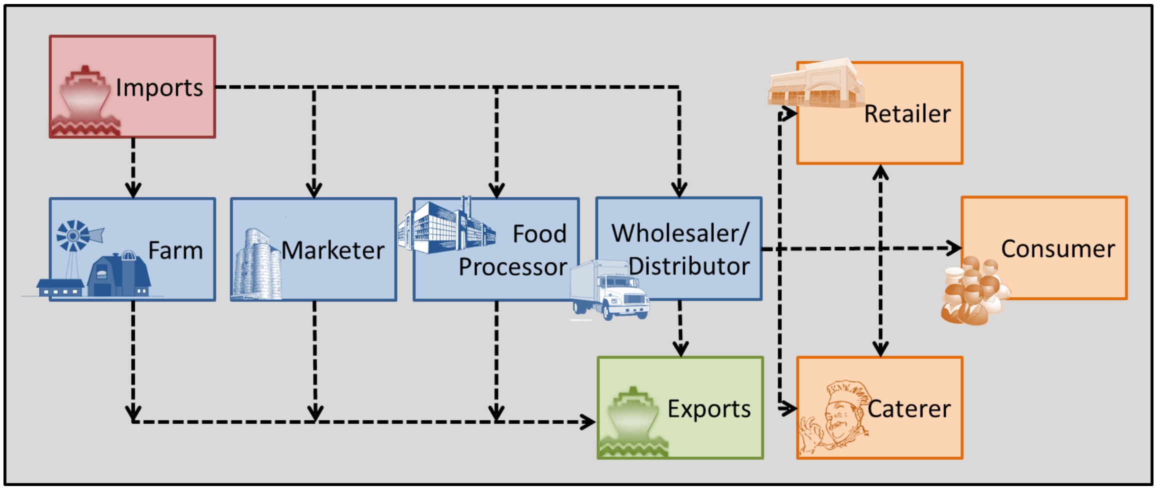


Figure 1.1 Illustration of food supply chain network [4]

The performance of a supply chain network is usually measured by metrics such as the rate of on-time delivery, cost-profit ratio, qualification rate, and demand-supply ratio, which are affected by the occurrence of risks. Moreover, since food is a necessity in everyone's life, keeping the food supply chain running steadily without major disruption is the target for decision makers. Therefore, with supply chain disruption cases like Hurricane Sandy that affected the Port of New York and New Jersey in 2013 and delayed a lot of shipments for months [5], decision makers have realized the criticality of food supply chain risk management.

Food supply chain is unique comparing to the supply chains in other industries. The food supply chain not only suffers from common risks in all supply chains such as financial risk and natural risks, but also needs to handle risks unique to the food industry such as food safety and food deterioration. All activities related to food production and handling including cultivation, food processing or even transportation may be vulnerable. Food supply chain risk is one potentially negative influence of one or more components, which may spread outward to the entire network. Food risks would have serious impacts on the health and safety of consumers. Therefore, it is important to analyze the risks in New Jersey food supply chain and develop strategies to prevent or mitigate the risks.

Based on the risk occurrence mechanism, there are three types of food supply chain risks: natural disasters, accidental risks, and intentional risks [6]. Natural disasters are the risks caused by earthquake, flood, tsunami, mud-rock flow, volcanic eruptions, etc. that make the components in the network not working properly. Natural disasters would cause irreversible destruction to all members in short term. For example, heavy snow in winter tends to last long and may seriously affect agriculture. Since the farm crop yields would dramatically decrease, the manufacturer would reduce its production outputs and then affect the entire supply chain. Accidental risks are the risks that happen by accident. The main accidental risks are quality risks caused by the high defect rate of products, management risks caused by defective organization structure, technology risks caused by deficiency of advanced manufacturing technique or equipment, and capital risks that result from shortage of funds or overdue payments. This kind of risk cannot be avoided but can be mitigated after they occur. It is also desirable to correctly identify these accidental risks so that preparation plans can be made in advance. Intentional risks are the risks that are caused and planned intentionally by human beings. They are mainly the societal risks (such as labor strike, riot, terrorist attack), legal risks (such as the influences of law amendment), and, more recently, cybersecurity risks. These risks will result great financial loss and negative social impact. But they can be prepared for, controlled, and even be avoided by taking preventive actions. For example, if the Port Authority had reinforced better communication with the port workers in NJ to satisfy their needs, the labor strike in 2016 might not have happened.

In sum, the New Jersey food supply chain is vulnerable due to its complexity and the existence of various risks. It is even more dangerous when multiple units are affected by risks at the same time or when risks propagate throughout the network.

1.2 Problem Description

The Department of Homeland Security (DHS) has defined 16 critical infrastructures for the nation to strengthen and maintain their security, functionality and resiliency [7]. However, DHS did not define the specific critical assets in each state. In alignment with the DHS, New Jersey Office of Homeland Security and Preparedness is interested in identifying the critical assets within New Jersey so that they could prepare, plan, allocate resources to ensure the functioning of NJ supply chains. Since the food industry plays an important role in New Jersey, NJ Office of Homeland Security and Preparedness prioritizes the food supply chain network as the first system to be investigated. We are motivated to develop a systematic approach for risk analysis and management for New Jersey food supply chain network. Our work is timely to provide NJ Homeland Security with insights into the risks in NJ food supply chain.

In order to identify the critical assets of the food supply chain network, we first need to establish the supply chain configuration. Such a configuration consists of the major players in the food industry and their relationship, represented as nodes and links, respectively, along with risks and failure probabilities. Since the food supply chain is vast and complex, no existing configuration on NJ food supply chain network can be found in literature.

To ensure that all assets in the food supply chain function smoothly and that the network is robust to disruption, we need to know what the potential risks are and understand how they impact the assets. Ideally, all assets within the network should be in good health condition. Any underlying possibility that would deteriorate the assets or the network must be identified and eliminated in time. An effective method for identifying the risks and vulnerable assets is in need.

Furthermore, we also need to understand how different assets in NJ food supply chain interact with each other. All nodes in the network are directly or indirectly connected. Thus, risks always propagate along the linkage relationship and create a ripple effect. Understanding the relationship between assets and how risks propagate through the network will provide us with important insights into the vulnerability of critical assets.

After understanding the risks and their propagation mechanism, simulation can be developed to mimic how the NJ food supply chain performs under various risks. By analyzing the simulation results from different scenarios, we aim to develop risk mitigation plans and preparation strategies.

1.3 Thesis Outline

This thesis is organized as follows. Chapter 2 reviews the existing studies on supply chain risk modeling and risk propagation. Chapter 3 builds a NJ food supply chain configuration by defining the important nodes, links, risks, and failure probabilities. Chapter 4 proposes a model for risk propagation for New Jersey food supply chain based on the traditional virus propagation models. The proposed method is implemented in simulation and Chapter 5 shows the simulation results that demonstrate how risks propagate through the network and which assets are the most vulnerable ones in the NJ food supply chain. Finally, Chapter 6 concludes the thesis and outlines future efforts.

CHAPTER 2

Literature Review

There is a vast body of literature on supply chain risk identification and assessment. The literature on the following two topics are reviewed in this chapter: (1) supply chain risk modeling by integrating the supply chain elements and risk factors into the network, and (2) risk propagation modeling to assess the influence of risk dissemination.

2.1 Supply Chain Risk Modeling

Supply chain risk modeling has been studied based on two main aspects: (1) the element structure of the supply chain and (2) risk factors.

For the supply chain element structure, many studies aim to construct the supply chain based on the roles of components in the network. A typical supply chain consists of five major elements: supplier, manufacturer, distributor, retailer, and customer [8]. Figure 2.1 shows all the elements in the supply chain. These elements in the network connect with each other and may impact each other. For example, Vrijhoef and Koskela [9] studied the roles of supply chain management in construction. Chiu and Kremer [10] studied supply chain network models by focusing more on specific industries and investigated the five layers supply chain structure to find out the critical layers for the bicycle industry.

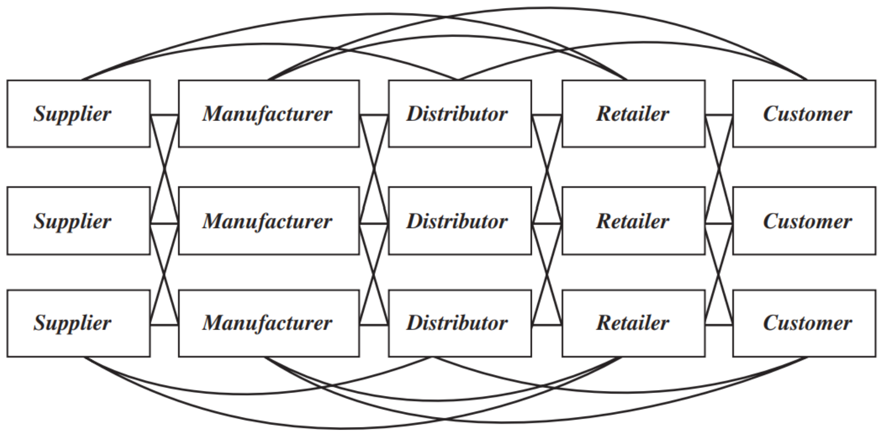


Figure 2.1 Supply chain elements [8]

Moreover, some researchers developed quantitative methods to construct the risks in supply chains. Thaheem, Marco and Hurtado [11] reviewed the quantitative analysis techniques for construction project risk management. Ouabouch and Amri [12] built a Supply Chain Risk Factors (SCRF) matrix based on the data collected from a sample of Moroccan Pharmaceutical Industry, and identified the critical risk factors which should retain main attention in that industry. Figure 2.2(a) shows the probability of and impact values of each supply chain risk factor in pharmaceutical industry. The most critical risks are the ones on the top right of the matrix in Figure 2.2 (b), which have the highest probability and the greatest impact.

	Code	Risk Factor	Probability	Impact
Upstream	*UpR1*	Supplier failure	**3,06**	**3,94**
	UpR2	Supplier quality problems	2,47	**4,38**
	UpR3	Increasing in RM prices	**3,00**	**3,73**
	UpR4	Unpredictable Trade barrier	2,35	3,53
	UpR5	Upst. transportation failure	2,12	3,53
Internal	*IR1*	Machine breakdown	2,06	3,00
	IR2	Outage of IT System	2,06	**3,12**
	IR3	Accident	2,06	3,00
Downstream	*DwR1*	Unexp. demand fluctuations	**2,41**	**3,93**
	DwR2	Inventory shortage(*)	**2,81**	**4,06**
	DwR3	Delivery chain disruptions	2,18	3,60
	DwR4	Decline in market prices(*)	1,94	3,41

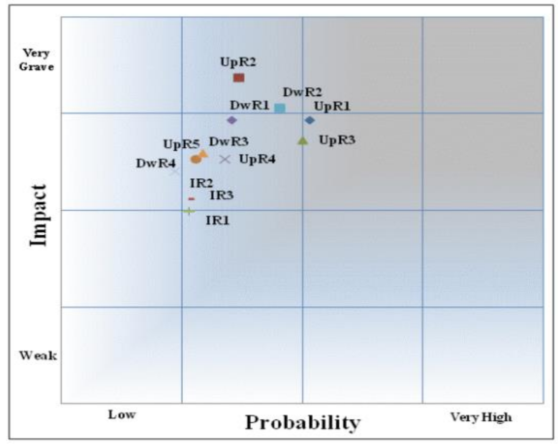


Figure 2.2 (a) SCRFs probability and impact values (b) Supply chain risk matrix for pharmaceutical industry [12]

Wagner and Neshat [13] developed a Supply Chain Vulnerability Index (SCVI) to measure the vulnerability of supply chain. In order to calculate the index, they proposed a 4-step algorithm which consists of finding graph nodes, finding graph's weighted and directed edges, calculating adjacency matrix permanent, and comparing different SCVIs. In their model, the adjacency matrix of a simple graph is a matrix with rows and columns labeled by graph vertices, with a 1 or 0 in position (D_i, D_j) according to whether D_i and D_j are adjacent or not. Figures 2.3 (a) and (b) illustrate the weighted directed graph and its adjacency matrix. The three nodes and edges represent the vulnerability drivers and the interdependencies between them, respectively. When the risks happen, they can transfer from one node to the others along the edges if they are connected. Such relationship can also be presented in the corresponding adjacency matrix.

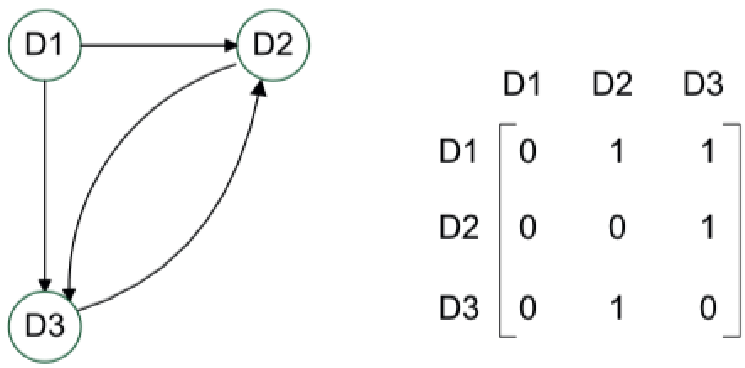


Figure 2.3 (a) Supply chain weighted directed graph for risk factors (b) Supply chain risk factor matrix [13]

Singh and Acharya [14] developed an influence matrix to investigate the supply chain flexibility by using an expert evaluation method for a fast-moving consumer goods company. They designed questions and asked the experts to evaluate the mutual relationship using a scale from 0 to 4 (0 for no influence and 4 for very high influence). After collecting the answers from various firms, they created an initial direct-relation matrix (Table 2.1) which represents the influence score between any of the two elements in the supply chain.

Table 2.1 Direct influence matrix [14]

Supply chain fexibilities	Manufacturing	Sourcing	Coordination	Information system	Logistics	Access	Market	Expansion	Distribution	Demand management	Transshipment	New product development	SUM
Manufacturing	0.00	3.25	3.35	2.85	2.8	1.20	2.45	3.00	1.40	3.0.2	1.15	1.2	22.85
Sourcing	1.9	0.00	3.15	3.70	3.30	1.20	3.45	1.00	1.30	1.30	1.50	1.2	23
Coordination	3.50	3.00	0.00	3.60	3.45	2.7	3.2	1.5	2.8	1.1	3.15	2.5	30.5
Information System	2.75	3.12	3.85	0.00	3.45	2.65	3.2	1.75	3.00	3.20	2.35	2.85	32.17
Logistics	2.00	2.40	1.6	1.00	0.00	2.90	3.80	2.65	3.70	3.45	3.25	0.50	27.75
Access	0.70	2.50	2.90	1.7	2.70	0.00	3.6	3.15	2.85	2.60	0.60	0.80	24.1
Market	2.95	3.15	3.4	1.50	3.45	1.2	0.00	2.85	3.8	2.95	3.25	1.00	29.5
Expansion	3.00	3.65	3.4	2.45	2.8	2.75	2.9	0.00	2.7	3.15	1.6	3.00	31.4
Distribution	1.1	0.80	1.2	2.6	3.15	0.6	3.5	2.85	0.00	3.15	2.8	1.3	23.05
Demand Management	3.5	3.2	2.3	3.4	2.65	2.70	2.95	2.15	3.15	0.00	3.45	3.6	33.05
Transshipment	0.25	0.30	2.6	3.1	3.4	1.15	3.6	1.7	1.15	2.35	0.00	0.25	19.85
New Product Development	1.15	1.2	2.35	2.75	0.35	0.75	1.15	2.95	1.75	3.1	0.65	0.00	18.15
SUM	22.8	26.57	30.1	28.65	31.5	19.8	33.8	22.7	27.6	29.55	26.9	18.2	

2.2 Supply Chain Risk Propagation

In today’s dynamic and connected environment, a decision taken by one firm in a supply chain network has direct and indirect effects on other companies. The effect from a risk source can be followed outwards incrementally, affecting the other nodes in the network. This is known as the ripple effect. Since the node in a supply chain network has direct or indirect connection with each other, it is generally believed that risks can spread out throughout the entire network after a certain period and affect the performance of the entire network.

The most widely used method in risk propagation is Bayesian network modeling. Bayesian network theory is used to analyze multi-echelon network faced with simultaneous disruptions. Chen, Xi, and Jing [15] built a Supply Chain Reliability and Resilience (SCRR) model based on a small chain of simple buyer supplier relationship, and demonstrated the modeling feasibility based on Bayesian Network. Ojha *et al.* [16] modeled supply chain risks propagation as a cascading effect in the entire network. Figure 2.4 shows the dependency of several risks for the suppliers in a supply chain network. Similar networks of the risk factors for manufacturers, distributors, and retailers were also provided in [16]. However, the Bayesian network theory emphasizes more on the risks factors themselves, as it describes how a risk flows and triggers other risks in the network. Also, it treats risk propagation as a one-way cascading problem. In most cases, however, the participator usually spreads the risks in multidirectional ways to its neighbors. For example, a labor strike of a manufacturer would not only affect the goods supply to the downstream distribution center and retailer, but also bring payment issues to the upstream suppliers.

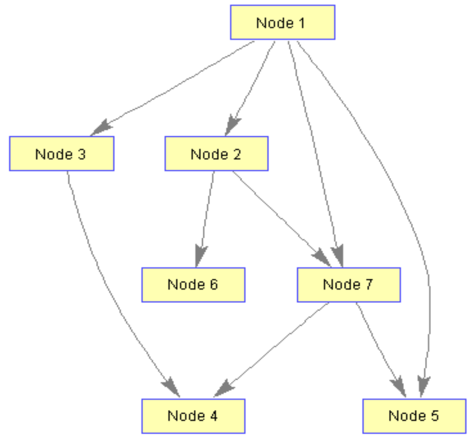


Figure 2.4 Network of risk factors for suppliers [16]

Some existing studies focus on how members in the network spread risks along the links that connect these components, even if the components are in different stages. Figure 2.5 depicts a general supply chain network with multiple layers made by Vorst *et al.* [17]. Each player in the network is represented as a node in its layer. A connected link between two nodes indicates that risks can propagate along the link to influence the performance of the network. William and Stephen [18] considered the network relationship between enterprises and built dynamic models in conformity with the propagation characteristics of risks between firms. Then they analyzed the risk transmission path, influential factors, and proposed risk control strategies. From a system perspective, what happens between two companies does not solely depend on the two parties involved, but on what is going on in a number of other relationships [19]. Therefore, the analysis of a supply chain network should preferably be evaluated within the context of the complex food supply chain network.

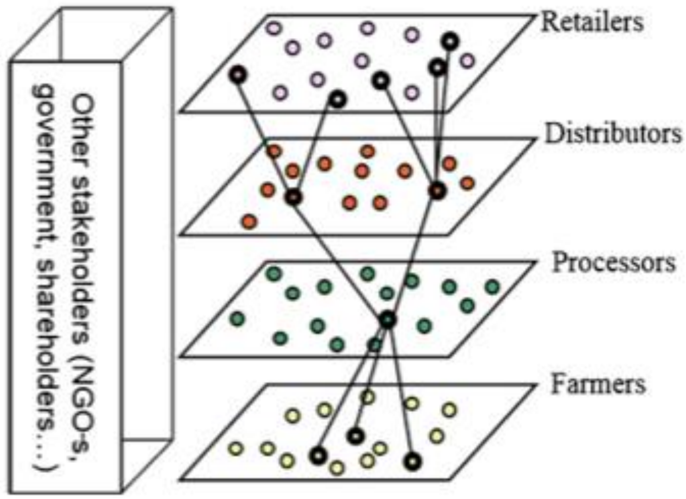


Figure 2.5 Schematic diagram of a supply chain [17]

Some researchers developed risk propagation models by extending the propagation models from other fields. Yang and Zhang [20] developed an SIR risk propagation model for supply chain risk management based on the susceptible-infected-susceptible (SIS) model in biology. The SIR risk propagation model describes how the states of nodes in supply chain change among susceptible (S), infected (I) and recovered (R). It can reflect the propagation of risks in supply chain network to a certain extent, but does not consider all the states that the real supply chain may have. For example, it assumes the recovered nodes will be immune to the risks forever, but in real life, companies cannot resist the same risks all the time. There are also studies on introducing more indicators to analyze the complex food supply chain. Li, Du, and Zhang [21] used SIR Model to analyze the status change for agri-food supply chain based on [20]. It was assumed that when a node was affected by risk, it would spread the risk to its neighboring node with probability α. Simulation experiments were conducted for three scenarios with $\alpha = 0.75, 0.5, 0.25$. The result is shown in Figure 2.6., where the vertical axis is the risk interference density $l(t)$ at time *t*. All three curves in Figure 2.6 first sharply increase and then gradually decrease.

These results indicate that although the α value is different, their trends of risk spread are the same. Figure 2.6 also indicates that there are three stages in risk propagation: in the initial stage, the risk only affects its originating node and propagates slowly; in the middle stage, the risk can no longer be contained in one node and starts to spread to neighboring nodes and further nodes in the network; in the last stage, the network reaches dynamic stability because of the immune mechanism. Therefore, risk propagation can be controlled by improving the anti-interference ability in the supply chain network. This model of risk interference trend demonstrates that all the risks could be covered at the end due to the immune mechanism, although they outbreak very quickly at first.

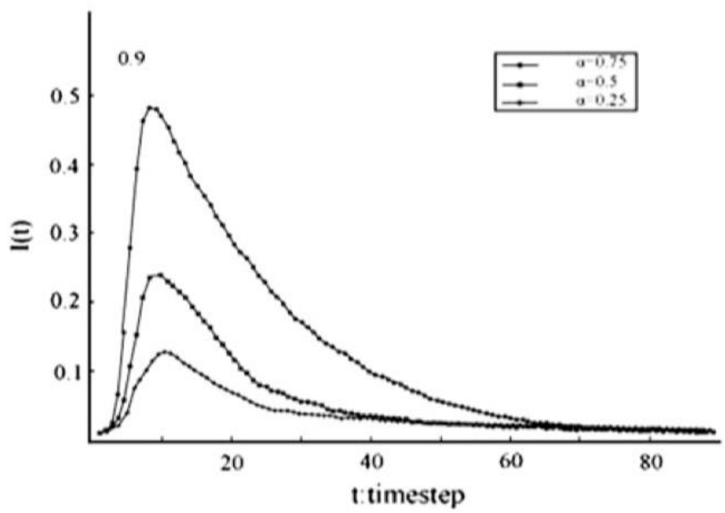


Figure 2.6 Trend of risk interference density over time for agri-food supply chain network [21]

2.3 Summary

In summary, there are a lot of literature on modeling supply chain risks. However, there are some limitations in the existing methods. Most of the current studies focus more on material supply and manufacturing process, rather than specific assets in the food supply chain. Moreover, the widely used Bayesian network theory focuses more on risks rather than how participators in supply chain are affected. Furthermore, although some authors take the geographic distance as a factor when dealing with supply chain cost problems [22], they seldom quantify such a factor. Finally, in most literature the transportation components are regarded as links. In order to evaluate how risks affect transportation infrastructure, these components should be modeled as nodes instead of links.

CHAPTER 3

Configuration Modeling of New Jersey Food Supply Chain Network

In this section, we build a configuration of New Jersey food supply chain network by identifying its components and links. Then we define the risks and failure probability for risk analysis and management. Section 3.1 introduces the five types of components: suppliers, transportation, manufacturers, distribution centers and retailers. To connect components into a network, the links connecting each pair of components if they have business relationship are defined in Section 3.2. The main risks and failure probabilities are described in Section 3.3. The network and risks are then integrated to construct the configuration of NJ food supply chain.

3.1 Identification of Key Components in NJ Food Supply Chain Network

There are five types of key components in New Jersey food supply chain: suppliers, transportation, manufacturers, distribution centers (DCs) and retailers. We choose 293 components to constitute NJ food supply chain network, including 60 suppliers, 148 transportations, 45 manufacturers, 17 DCs, and 23 retailers.

Suppliers: Food suppliers are the organizations including farms or fisheries that provide edible raw materials to manufacturers or end customers. For food supply chain, the vendors who offer meat, crops and sea food are the sources and starters of the whole chain. In New Jersey there are nearly 10,300 farms and hundreds of large fishery suppliers — a huge number that could not be identified easily. Instead, we divide them into six groups according to their regions and select several big farms as representatives. As shown in Figure 3.1, the six regions are Delaware River region, Gateway region, Greater Atlantic

City region, Shore region, Skylands region and Southern Shore region. Most of the farms are concentrated in Delaware River region, Shore region, and Skyland region.

Figure 3.1 NJ supply chain network – suppliers

Transportation (Roads, Railway, Bridge, Port, Airport): In order to find out the critical assets in NJ Food supply chain, we consider transportation as nodes instead of links. Transportation is important, as it connects all other components in the network. In New Jersey supply chain, the major transport modes are in-state and interstate roads, bridges and tunnel, ports and airports. They are funded and maintained by the government to keep their normal functions. Among them, roads and railways are more critical than the others, as according to the report of New Jersey department of transportation, on a tonnage basis, about 84% of food is moved by road and 11% food is moved via railway in New Jersey [23]. Figure 3.2 shows the transportation nodes in this study. There are 11 interstates roads, 44 inner state roads, 11 US roads, 50 bridges, 25 railways, 20 ports, and 12 airports in NJ.

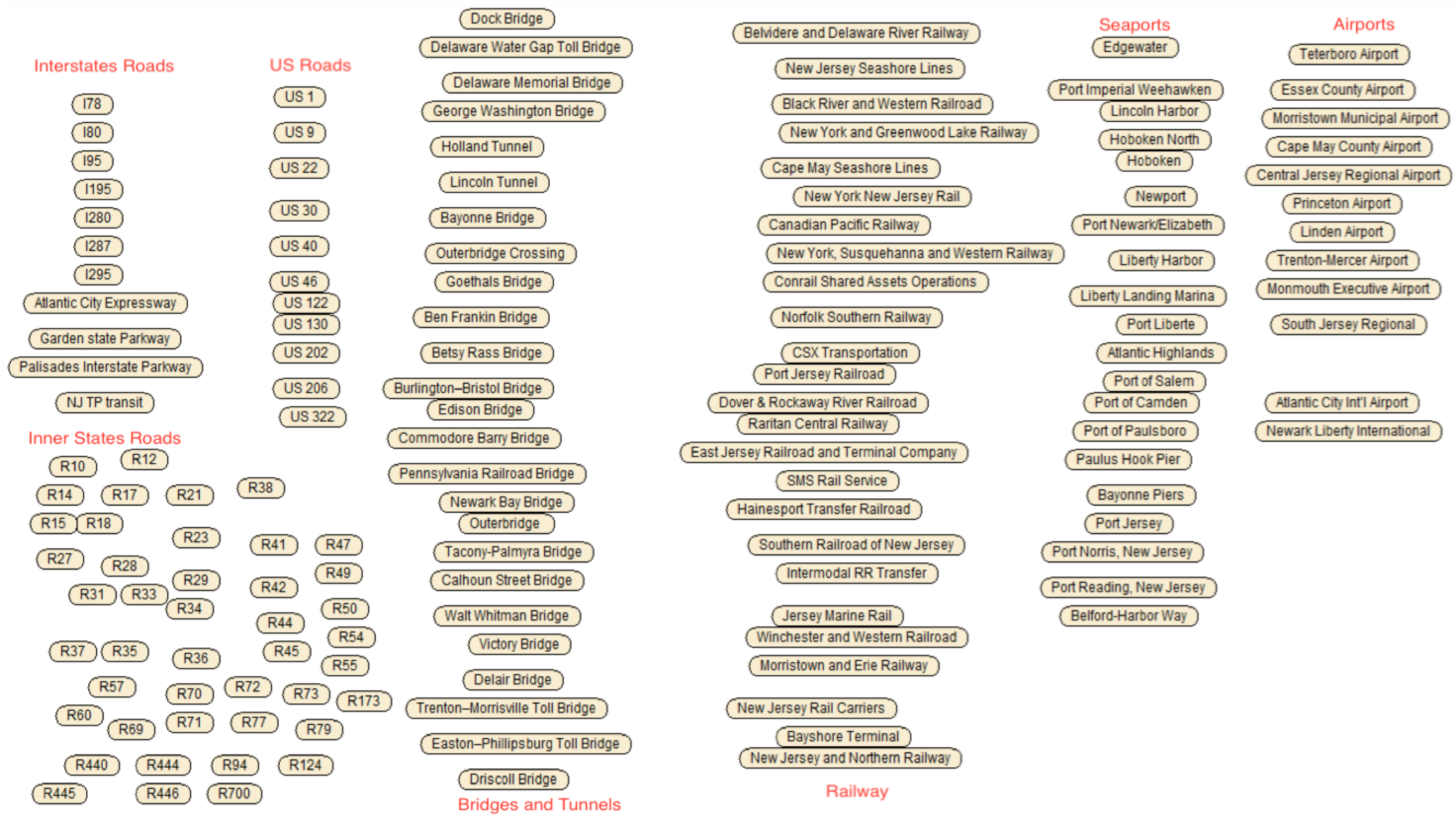


Figure 3.2 NJ supply chain network – transportation

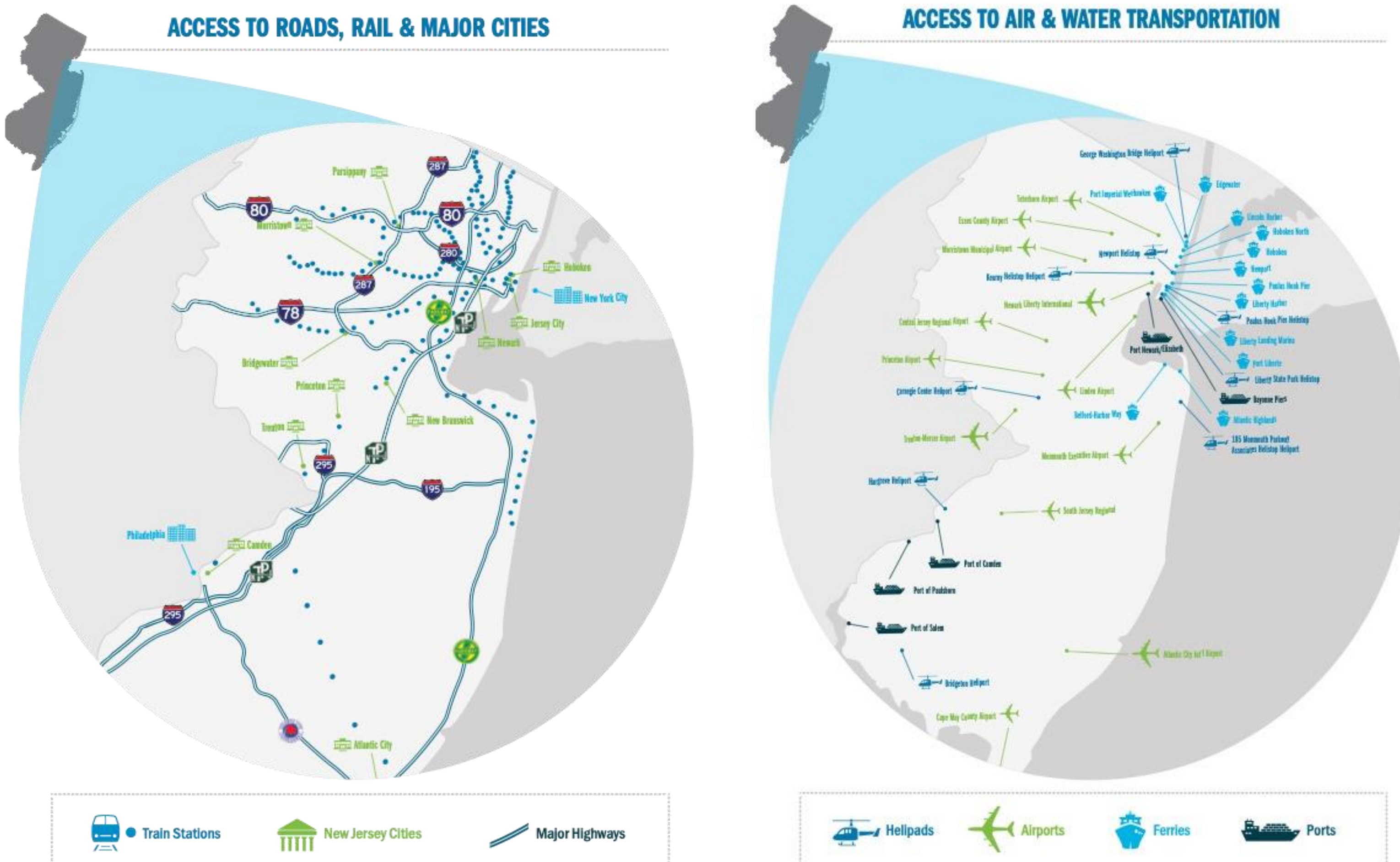
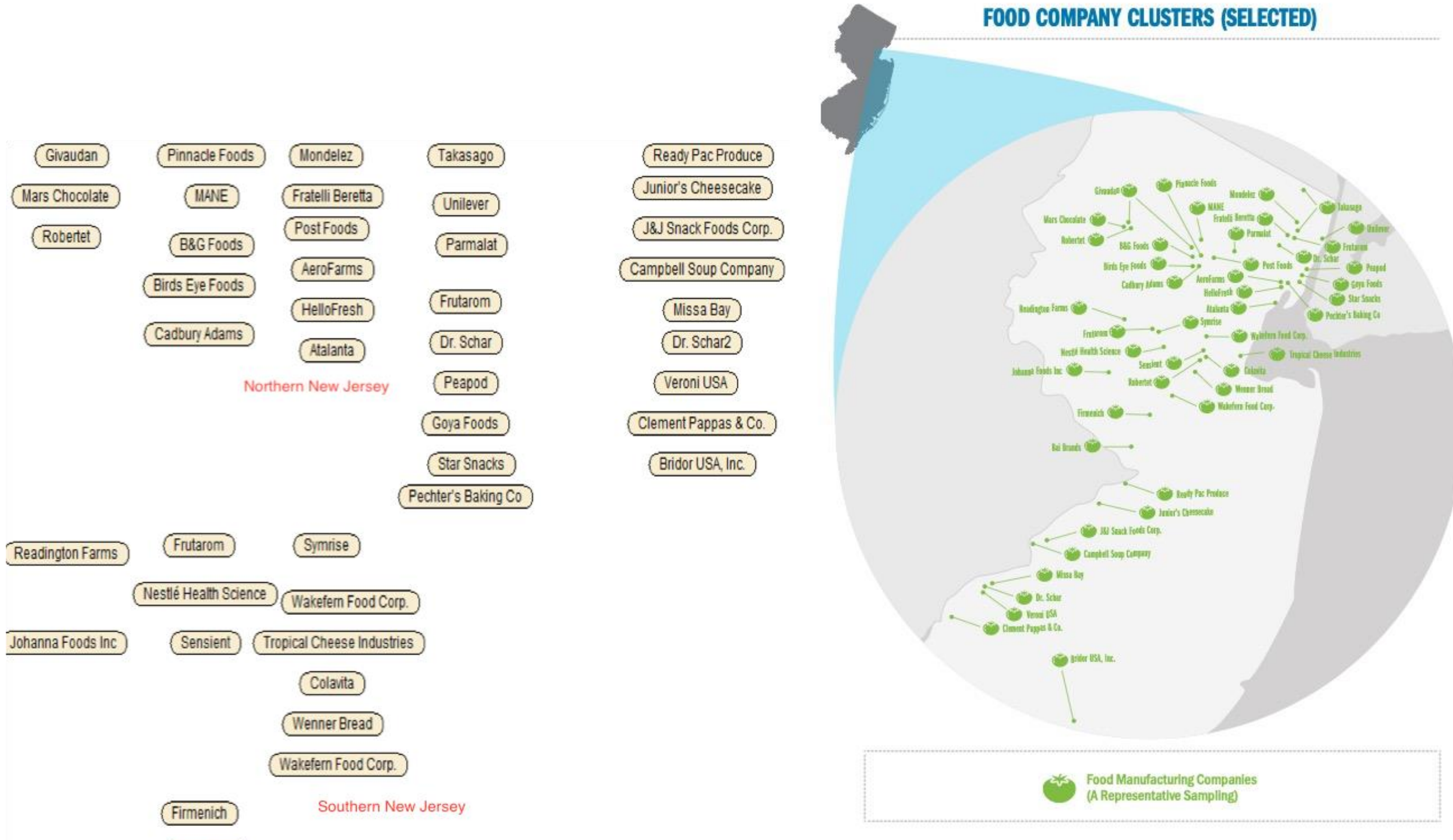


Figure 3.3 Map of NJ roads, rail, air, and port distribution [24]



(a) (b)

Figure 3.4 (a) Distribution of NJ food manufacturers (b) Map of NJ food manufacturers [24]

Moreover, Figure 3.3 shows that most of the transporation nodes are in the northern New Jersey. The reason is that this area is very close to New York City and costs are relatively cheap with complete infrastracture so manufacturers and suppliers prefer to build their factories in this region.

Manufacturers: Food manufacturers are the factories who transform edible raw materials into food products that can be sold through certain processes. In this work, 45 key manufacturers are selected. Figure 3.4 shows that the distribution of NJ food companies is almost the same as the distribution of transportation utilities, as the manufacturers are inclined to build their plants near the places with convenient transportation. The majority of manufacturers are located in northern New Jersey where they can access New York City more easily.

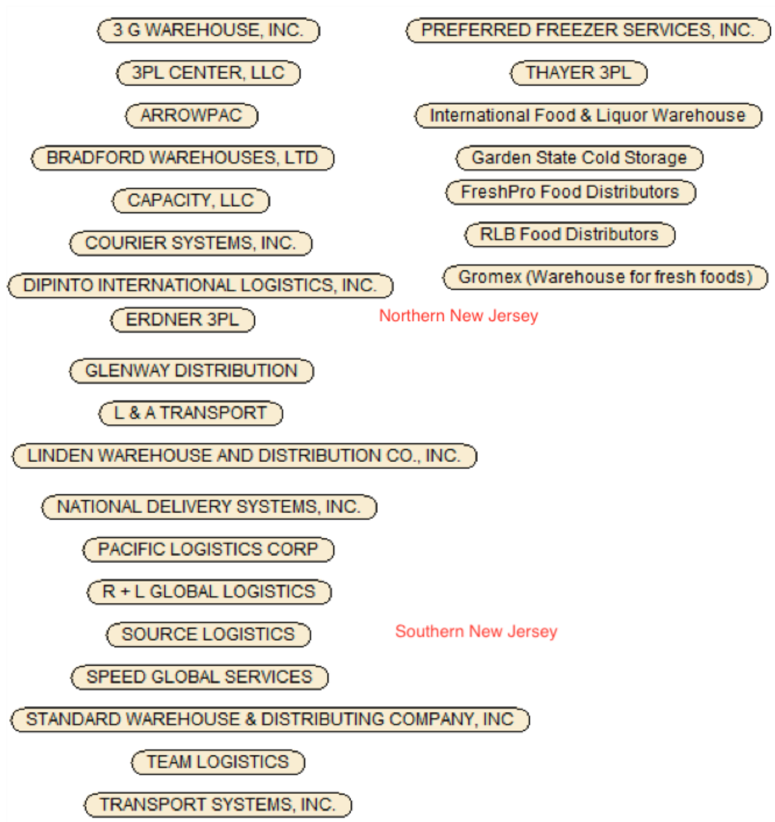


Figure 3.5 NJ supply chain network – distribution center

Warehouses and DCs: A distribution center for a set of products is a warehouse or other specialized building, often with refrigeration or air conditioning, which is stocked with products (goods) to be redistributed to retailers, to wholesalers, or directly to consumers. As the intermedia of manufacturers and retailers, they must be close to these two components.

Figure 3.5 shows the representative distribution centers. One warehouse or distribution center has to fulfill the demands of its local retailers. They have strong linkage with these retailers and manufacturers.

Retailers (Walmart, Costco, Shoprite based on regions): Retailers are the business units who sell goods to end customers in relatively small quantities for consumption. Since the distribution centers need to deliver the food to their retailers in the surrounding areas, the retailers have more business transactions with the nearby distribution centers.

3.2 Links in New Jersey Food Supply Chain Model

To build the New Jersey food supply chain configuration, besides the components mentioned above, we also need to establish the relationship between every pair of components. The links where risks can spread along should be identified.

3.2.1 Links Between Different Component Types

To represent the reality of the food supply chain, the links in the network have the following characteristics:

First, different from the goods flow where there is only one direction, the risk diffusion has both forward and backward directions. Existing studies of supply chain focus more on the goods movement, which is a forward flow. But when it comes to the risk assessment, more factors have to be considered. For example, unlike the goods flow, the money that consumers pay for food moves from consumers to producers in the reverse process. The goods, capital, and information flows that connect farmers and consumers are illustrated in Figure 3.6. Once a risk occurs, it will influence the goods flow in the forward direction as well as the capital and information flows in the backward direction.

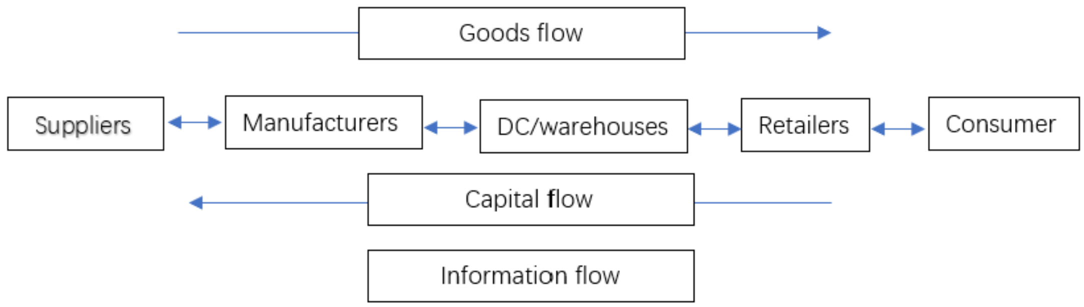


Figure 3.6 Capital, information and goods flow

Moreover, the members not only spread the risk to the members of the other type, but may also indirectly interact with other nodes of the same type. For example, if one major manufacturer has some capacity issues, the unmet capacity would have to be covered by the other producers in order to meet the stable food demands of local people. Such risks would appear at one member and then quickly spread out to the others.

Furthermore, risks can also disseminate across the processes with direct connections. For example, if the capacity of one manufacturer is reduced because of labor strike or sudden technical failure, it would impact the supply of distribution center. The manufacturer would also bring risks to the retailer who the manufacturer has a direct business relationship with.

Based on the description above, a 5-stage model for NJ food supply chain model has been developed, as shown in Figure 3.7, where each block represents one type of components. This network is directed with spreading risks that could be initialized by any node.

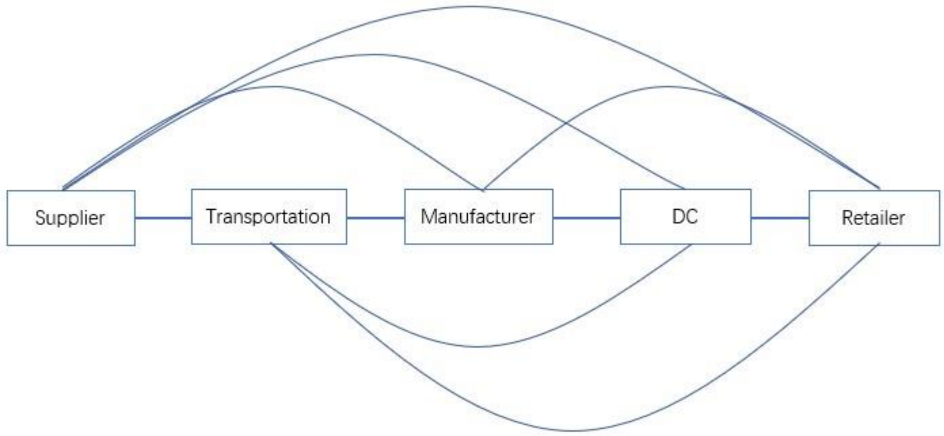


Figure 3.7 Links between different component types in NJ supply chain network

3.2.2 Connection Matrix

We create a connection matrix to reveal the connection relationship of every pair of nodes in the network. Two factors are considered in the connection matrix: distance factor and influence factor.

The distance factor in the connection matrix is the geographical distance between two nodes. Most food is perishable and is categorized as fast-moving consumer goods that require to be shipped to the end customers as soon as possible to expediate the whole cycle. Companies that are closer to each other are inclined to have more business. We use longitude and latitude collected from Google map to determine the location of each company. Denote (x_i, y_i) as the location of node i (i = 1,…, 293) and $d_{i,j}$ as the distance between node *i* and node *j*. $d_{i,j}$ can be calculated as

$$d_{i,j} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{3.1}$$

Table 3.1 illustrates the geographical distances between some pairs of nodes in the network. All the diagonal values are 0 because the distance of each node to itself is 0. Also, $d_{i,j} = d_{j,i}$ as the distance from node *i* to node *j* is the same as that from node *j* to node *i*.

The influence factor in the connection matrix reflects the degree of influence between two nodes. They are the directed influence among Suppliers, Manufacturers, DCs, Retailers and Transportation based on expert opinions as shown in Table 3.2. (The data are collected from experts who have worked over 6 years at Global Supply Chain Department of Lenovo.)

Table 3.1 A segment of distance matrix for the supply chain network

A	C	D	E	F	G	H	I	J	K	L	M	N	O	P
No.				1	2	3	4	5	6	7	8	9	10	11
	Longtitude	Latitude	Names	erry Grove Fa	pe's Garder	mwind Alpa	ombs Barnya	wtown Rode	ines Berry Fa	Jersey Fresh	on's Corner /	FarmLee Tu	sis Family Fa	s Discovery
1	40.3083691	-74.712445	Cherry Grove Farm	0	0.59872303	0.26504486	0.91431253	0.92667705	0.38719305	0.19694607	0.41285232	0.15375662	0.16253212	0.39010322
2	39.725298	-74.84845	Pope's Gardens	0.59872303	0	0.335404	0.4244383	0.53013287	0.30415141	0.71498247	0.19430652	0.61126608	0.52493827	0.2280751
3	40.046061	-74.750435	Stormwind Alpacas	0.26504486	0.335404	0	0.68876089	0.73385378	0.17029744	0.40875879	0.16179903	0.28847462	0.20583976	0.15324912
4	39.5616609	-75.2400758	Coombs Barnyard	0.91431253	0.4244383	0.68876089	0	0.16661001	0.71788259	0.95773018	0.52841472	0.97640821	0.89458726	0.53694656
5	39.6600264	-75.3745493	Cowtown Rodeo	0.92667705	0.53013287	0.73385378	0.16661001	0	0.79744579	0.93526674	0.58405086	1.01200351	0.93605096	0.58167595
6	39.9312614	-74.6246484	Haines Berry Farm	0.38719305	0.30415141	0.17029744	0.71788259	0.79744579	0	0.56020612	0.22699431	0.34069043	0.25862339	0.24781288
7	40.4402062	-74.8587554	resh Vegetables an	0.19694607	0.71498247	0.40875879	0.95773018	0.93526674	0.56020612	0	0.52067598	0.34167756	0.35909959	0.48817686
8	39.919583	-74.8513421	ohnson's Corner Far	0.41285232	0.19430652	0.16179903	0.52841472	0.58405086	0.22699431	0.52067598	0	0.45023547	0.36686924	0.038381
9	40.2665952	-74.5644719	rkey FarmLee Turke	0.15375662	0.61126608	0.28847462	0.97640821	1.01200351	0.34069043	0.34167756	0.45023547	0	0.08637519	0.43949777
10	40.1889116	-74.6022334	Oasis Family Farm	0.16253212	0.52493827	0.20583976	0.89458726	0.93605096	0.25862339	0.35909959	0.36686924	0.08637519	0	0.35857848
11	39.9521977	-74.8715753	Paws Discovery Farm	0.39010322	0.2280751	0.15324912	0.53694656	0.58167595	0.24781288	0.48817686	0.038381	0.43949777	0.35857848	0
12	39.9435796	-74.4985978	e Barrens Native Fru	0.42284986	0.41236321	0.27189044	0.83405726	0.92070269	0.12665106	0.61347492	0.35355958	0.32966419	0.26632335	0.37307705
13	39.89092	-74.968664	Springdale Farms	0.48980805	0.20465105	0.26775479	0.42670355	0.46696331	0.34637286	0.56017429	0.1207725	0.551818	0.47230327	0.11480929
14	39.7083459	-75.1331269	nmit City Farms&Wir	0.73280359	0.28518119	0.51039649	0.1815339	0.24621038	0.5551952	0.78160042	0.35217011	0.79687564	0.71609448	0.35759326
15	40.331905	-74.725875	Orchards Vineyard&	0.02709803	0.61886726	0.28689717	0.9261093	0.93391606	0.41323373	0.17142447	0.43098889	0.17411585	0.18903533	0.40670162
16	40.37865	-74.5305225	un's Country Farm&M	0.19502615	0.72659943	0.39871914	1.08209846	1.10851302	0.45718294	0.33395509	0.56006047	0.11708476	0.20283765	0.5460573
17	41.057612	-74.062474	's Farm Stand&Greer	0.99188065	1.5468739	1.2233257	1.90384235	1.91697342	1.25885096	1.00759813	1.3847104	0.9368615	1.02273193	1.36988528
18	40.3158713	-74.3869596	Etsch Farms	0.32557185	0.74949997	0.45267203	1.13870127	1.18552349	0.45212912	0.48790413	0.61048794	0.18422473	0.24992314	0.60589674
19	41.0817566	-74.3245526	Farmstead Estate	0.86521023	1.45411431	1.11983981	1.7745066	1.76743029	1.18898978	0.83484103	1.27599164	0.84973489	0.93502878	1.25504468
20	40.4226327	-74.4596285	marese Farm&Orcha	0.27743892	0.79840957	0.47578847	1.1620544	1.19107029	0.51834093	0.39951359	0.63757238	0.18798894	0.27379136	0.62530733
21	39.6406034	-74.7270219	rms&Blueberry Plant	0.66792478	0.14804715	0.40613303	0.51909173	0.64781864	0.30815971	0.81038161	0.30542614	0.64675207	0.56232913	0.34349191
22	39.501708	-74.574461	B&B Farms	0.81837749	0.35364171	0.57209006	0.66830937	0.81560162	0.43247532	0.98061316	0.50128102	0.76495242	0.68776456	0.53964607
23	41.0585142	-74.1243213	Fox's Cranberries	0.95320887	1.51717758	1.19041163	1.86694347	1.87585665	1.23329886	0.96005116	1.35119337	0.9060178	0.99227449	1.33503735
24	40.3619126	-74.1956763	A. Casola Farms	0.51953517	0.91180681	0.6383725	1.31574051	1.37200065	0.60784662	0.66768539	0.79091916	0.38091417	0.44183484	0.7903833
25	40.1336996	-74.0690478	Atlantic Farms	0.66668538	0.87992026	0.68700003	1.3032785	1.38877661	0.59133176	0.84710353	0.81106738	0.51293887	0.53603661	0.82279604
26	40.2597322	-74.3132582	Battleview Orchards	0.40213884	0.75633999	0.48659936	1.16029927	1.21901019	0.45261123	0.57457642	0.63658131	0.25130743	0.29752685	0.63741309
27	40.147023	-74.484506	Bullock Farms	0.27926466	0.55705225	0.28444957	0.95578999	1.01456531	0.25727993	0.47541456	0.43162215	0.14384734	0.12495757	0.43333537
28	40.28299	-74.173561	Delicious Orchards	0.53948129	0.8754973	0.62363368	1.28754398	1.35294366	0.57200774	0.7029995	0.76905908	0.39125455	0.43887444	0.77242961
29	40.0675093	-74.4893056	Dewolf's U-Pick Farm	0.32833616	0.49607789	0.26200877	0.90528366	0.97452487	0.19204469	0.52478199	0.39109157	0.21280312	0.16580472	0.39928297
30	40.2957453	-74.1459828	Eastmont Orchards	0.56660285	0.90491452	0.65399137	1.31754294	1.38329829	0.60163882	0.72726455	0.79939341	0.41950311	0.46859156	0.80281345
31	40.0590546	-74.4664559	Emery's Berry Farm	0.35024043	0.50726025	0.28427621	0.91972183	0.99189572	0.20336167	0.54696932	0.40937723	0.22952176	0.1878786	0.41897509
32	40.0730027	-74.4941562	's U-Pick Farm&Gree	0.32100988	0.49640977	0.25769105	0.90435971	0.97244097	0.19266243	0.51746593	0.38874075	0.20596688	0.15847888	0.3962815
33	40.3692292	-74.1833308	storic Longstreet Fa	0.53260284	0.92575966	0.65272112	1.32999119	1.38635137	0.62175318	0.67914367	0.8052458	0.39471797	0.4560634	0.80473335
34	40.365845	-74.218203	easant Valley Laven	0.49757274	0.89861657	0.6209128	1.30035998	1.3547386	0.59503006	0.64485422	0.77460628	0.36021198	0.42282949	0.77330424
35	40.256447	-74.3160863	Wemrock Orchards	0.39974507	0.75201753	0.48261896	1.15606415	1.2149327	0.44828143	0.57293734	0.63243666	0.24859282	0.29400883	0.63335272
36	40.778839	-74.713608	Alstede Farms	0.47047134	1.06213512	0.73370282	1.32615643	1.29945567	0.8522333	0.36842902	0.870225	0.53351222	0.60034876	0.84159937
37	40.5671283	-75.062658	olink Dairy&Bakeho	0.4354371	0.86865604	0.60744904	1.02100038	0.95922367	0.77212637	0.24017804	0.68115294	0.58181572	0.59585123	0.64393497
38	40.7546158	-75.1516184	Farm in Harmony	0.62610653	1.07303598	0.81424691	1.19622995	1.11706049	0.97755299	0.42967678	0.88738133	0.76348223	0.78857157	0.84988172
39	40.799729	-74.927414	ard View Lavender F	0.5363266	1.07732877	0.7741686	1.27693775	1.22427611	0.91972984	0.36602001	0.88342737	0.64494854	0.69198289	0.84936874
40	40.7872316	-74.7586675	Ort Farms	0.48108816	1.06572223	0.74121632	1.31672985	1.28448509	0.86639835	0.36117062	0.87258391	0.55567454	0.61843225	0.84263265
41	41.062513	-74.706216	rm&Sunset Vista Co	0.75416962	1.34475814	1.01741338	1.5929731	1.55358877	1.13418846	0.64072929	1.15210701	0.8084408	0.87976803	1.12256125
42	40.6495926	-74.5068851	agner Farm Arboretu	0.39835706	0.98538677	0.65082021	1.3119314	1.31608603	0.72792026	0.40945741	0.80719554	0.38730253	0.47044477	0.78699339
43	41.185435	-74.589845	Andersen Farms	0.88559322	1.48286095	1.15063559	1.74912619	1.71541022	1.25465641	0.7922618	1.2925796	0.91919006	0.9966004	1.26500838
44	40.5816761	-75.0458962	Buzzing Acres Farm	0.43114547	0.87884495	0.61170324	1.03833363	0.97849427	0.77491225	0.23459627	0.69008592	0.57536539	0.59253745	0.65316983
45	40.8310335	-74.8438973	Donaldson Farm	0.53894135	1.10574487	0.79051694	1.32976096	1.28563182	0.9260993	0.39110963	0.9114809	0.62981676	0.68609181	0.87927154
46	40.39469	-74.870544	lper Family Farmste	0.18012937	0.66975652	0.36873887	0.91131292	0.89092758	0.52462435	0.04701803	0.47549487	0.33179573	0.33813507	0.4424935
47	40.704622	-74.94865	Grochowicz Farms	0.46131244	0.98443666	0.68774398	1.17952917	1.12808252	0.83848891	0.27927899	0.79104681	0.58263221	0.62125814	0.75636158

Table 3.2 Original influence matrix

	Supplier	Transportation	Manufacturer	DC	Retailer
Supplier	1	0.5	4	0.5	0.5
Transportation	1.5	0.5	1.5	1.5	1.5
Manufacturer	3	0.5	1.5	3	1
DC	1	0.5	2	1.5	3
Retailer	1	0.5	1	3	2

With the expert views, the relationship between any two nodes is evaluated using a scale from 0 to 5 (0 for no influence and 5 for very high influence). It is noted that node A's influence imposed on node B is not always the same as the impact of B on A. For example, as shown in Table 3.2, the influence that the supplier brings to the manufacturer (e.g., shortage in supplies) has different degree of influence, compared with the influence the manufacturer brings to the supplier (e.g., payment issue). The other feature is that the influence degree of two nodes has positive correlation with their positions in the supply chain. That is, the closer they are, the greater the impact they have. For example, influence degree from supplier to manufacturer is 4 which is greater than the value from supplier to distribution center. Denote $f_{i,j}$ as the influence between node *i* and node *j* (*i*, *j* =1,…, 293). Based on the distance and influence factors, a connection matrix **C** is created as shown in Equation (3.5), where $c_{i,j} = N(\frac{f_{i,j}}{d_{i,j}})$ represents the connection probability between two nodes. The reciprocal of $d_{i,j}$ is used to reflect that a closer pair of nodes usually have a stronger relationship. $N(\cdot)$ is a normalization function so that all $c_{i,j}{}'$s are from 0 to 1.

$$\mathbf{C} = \begin{pmatrix} 0 & c_{1,2} & c_{1,3} & \cdots & c_{1,293} \\ c_{2,1} & 0 & c_{2,3} & \cdots & c_{2,293} \\ c_{3,1} & c_{3,2} & 0 & \cdots & c_{3,293} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ c_{293,1} & c_{293,2} & c_{293,3} & \cdots & 0 \end{pmatrix} \tag{3.5}$$

3.3 Failure Probability in New Jersey Food Supply Chain Model

To analyze the failure probabilities for the NJ food supply chain, we need to identify the sources of supply chain risks and then quantify the risks in the form of failure probabilities. Some of these failure probabilities are collected from on-hand documents and records, such as disaster [25] or societal risks [26], so that the result can truly reflect the reality of the NJ food supply chain.

3.3.1 Type of Supply Chain Risks

Supply chain risk is the negative uncertainty caused by the complex relationships among the nodes in supply chain. In the process of exchanging resources or working with other units, the nodes may suffer from various risks generated internally or externally. Eight major risks in total are considered in our work, as described below.

Management risk: It is mainly the management problems caused by unreasonable organization structure, imperfect system, and policy problems that make companies shut down.

Financial risk: It mainly refers to the risk that an enterprise cannot operate properly due to unstable financial situation and capital break caused by the lack of funding and mistakes of operations and management.

Technological risk: It is the risk that an enterprise is in an inferior position in market competition due to the lack of scientific production process, advanced technology and equipment, that eventually lead to shut down. This risk happens more frequently in manufacturing enterprises if technology cannot be upgraded in time.

Natural risk: It is the risk that an enterprise cannot operate properly because of natural disasters such as earthquake, flood, tsunami, debris flow, volcanic eruption and so on. This is the common risk for nearly all nodes in the network. Almost all components in the network would be influenced by this risk. Its failure probability is calculated based on the total occurrence rate (probability) of various disasters according to the geographical location of each unit in the network. For example, if the number of days that a company was affected by a certain natural event in its area is 416 between 01/01/1990 and 01/31/2019 (10623 days), then the failure probability is 416/10623 = 3.9%.

Societal risk: It is the risk that results from societal disturbance events caused by human factors such as conflicts, riots, terrorist attacks, demonstrations and abnormal enterprises operation because of serious air pollution, viral infection, water and power interruption, fire and other incidents.

Market risk: With heavy competitive pressure among companies, the market situation changes rapidly, which easily leads to the mismatch between demand and supply, which results in overstock or out-of-stock goods. The bullwhip effect is a significant character of market risk.

Quality risk: It is the risk that due to the quality problems of products from upstream suppliers, the reputation and finance of the entire supply chain is exposed to great risks. For example, the outbreak of E.coli bacteria in 2018 affected many food enterprises and retailers [27].

Logistics risk: It is the risk of shipment delays, traffic jams or even inability to deliver goods in the process of transportation due to the impact of some emergencies. For example, in 2002 the labor strike on the west coast of the US led to the failure of delivering the cargos to the destination that resulted in great losses [28].

In accordance with the unique characteristics of the aforementioned risks in supply chain, we allocate the risks for each process of the food supply chain, as shown in Table 3.3. By doing so, we could target specific risks in order to manage them.

Table 3.3 Specific risks for the five node sets

	Supplier	Transport	Manufacturer	Distribution Center	Retailer
Management risk	√		√	√	√
Financial risk	√		√	√	√
Technology risk	√		√		
Natural risk	√	√	√	√	
Societal risk		√	√	√	√
Logistic risk				√	
Market risk				√	√
Quality risk		√	√		

3.3.2 Failure Probability

A failure probability table is created to show the probability of failure for each node. Table 3.4 shows a segment of the failure probabilities for components in the network. Since there are 8 risks that have been defined, we denoted $p_{i,r}$ as the probability of failure of node *i* when risk *r* happens *r*=1,…8. *i* = 1,…,293.

Table 3.4 A segment of logistic risks of NJ food supply chain assets

Names	Logistic risk
Cherry Grove Farm	2.97%
Pope's Gardens	2.44%
Stormwind Alpacas	3.37%
Coombs Barnyard	2.44%
Cowtown Rodeo	1.87%
Haines Berry Farm	2.46%
Jersey Fresh Vegetables and Fruits	0.47%
Johnson's Corner Farm	1.52%
Lee Turkey FarmLee Turkey Farm	2.62%
Oasis Family Farm	2.85%
Paws Discovery Farm	2.43%
Pine Barrens Native Fruits	3.98%
Springdale Farms	2.91%
Summit City Farms & Winery	3.43%
Terhune Orchards Vineyard & Winery	2.93%
VonThun's Country Farm & Market	2.00%

Some types of risks (e.g., natural disasters) are calculated based on the record from the Internet. For the other types of risk whose record is limited or confidential, their failure probabilities are based on our best estimation. For example, the failure probabilities under management risks are estimated based on our experience (it is assumed to be less than 0.4) and the size of the company (it is assumed that that a larger organization has a lower risk). For transportation components such as bridges and roads, we use the specific values from either of the two criteria below to quantify the failure probabilities of logistic risks.

(1) Remaining life range: Most of the facilities reliability rates could be calculated by their remaining lives because they were built up based on certain requirements. The corresponding failure probabilities could be looked up from Table 3.5, where, P stands for the failure probability. The failure probability increases with the increase of bridge age. β_i is used to represent the reliability of the bridge structure. A higher value β_i indicates more

reliable bridge, and vice versa. When the load effect S and resistance R follow normal distributions, the structural performance also follows normal distribution and β_i can be expressed by $\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}}$. It could be calculated by the following formula from where we can find the direct relationship between P and β_i [29]:

$$\beta_i = -\Phi^{-1}(P) \tag{3.1}$$

So, if a bridge has a required age of 50 years and 30 years remained, we can look up Table 3.5 and find the failure probability P to be 1.97 $\times 10^{-4}$ and its corresponding structural reliability index β_i to be 3.545.

Table 3.5 Reliability index of bridges with different ages [30]

Remaining lifetime	Age of the bridge [years]									
	10 years		20 years		30 years		40 years		50 years	
[years]	β_i	P	β_i	P	β_i	P	β_i	P	β_i	P
2	3.328	4.38×10^{-4}	3.153	8.09×10^{-4}	3.039	1.19×10^{-3}	2.954	1.57×10^{-3}	2.886	1.96×10^{-3}
5	3.517	2.19×10^{-4}	3.377	3.67×10^{-4}	3.282	5.16×10^{-4}	3.208	6.68×10^{-4}	3.149	8.21×10^{-4}
10	3.623	1.46×10^{-4}	3.515	2.20×10^{-4}	3.437	2.94×10^{-4}	3.375	3.70×10^{-4}	3.323	4.46×10^{-4}
20	3.697	1.09×10^{-4}	3.622	1.46×10^{-4}	3.563	1.83×10^{-4}	3.514	2.21×10^{-4}	3.471	2.59×10^{-4}
30	3.727	9.70×10^{-5}	3.669	1.22×10^{-4}	3.621	1.47×10^{-4}	3.58	1.72×10^{-4}	3.545	1.97×10^{-4}
40	3.743	9.08×10^{-5}	3.696	1.09×10^{-4}	3.656	1.28×10^{-4}	3.621	1.47×10^{-4}	3.589	1.66×10^{-4}
50	3.753	8.72×10^{-5}	3.714	1.02×10^{-4}	3.679	1.17×10^{-4}	3.648	1.32×10^{-4}	3.62	1.47×10^{-4}
60	3.76	8.48×10^{-5}	3.726	9.72×10^{-5}	3.696	1.10×10^{-4}	3.668	1.22×10^{-4}		
70	3.766	8.31×10^{-5}	3.735	9.38×10^{-5}	3.708	1.05×10^{-4}				
80	3.77	8.18×10^{-5}	3.742	9.12×10^{-5}						
90	3.773	8.07×10^{-5}								

Remaining lifetime	Age of the bridge [years]							
	60 years		70 years		80 years		90 years	
[years]	β_i	P	β_i	P	β_i	P	β_i	P
2	2.828	2.35×10^{-3}	2.777	2.75×10^{-3}	2.732	3.15×10^{-3}	2.692	3.56×10^{-3}
5	3.098	9.75×10^{-4}	3.053	1.13×10^{-3}	3.014	1.29×10^{-3}	2.978	1.45×10^{-3}
10	3.279	5.22×10^{-4}	3.239	6.00×10^{-4}	3.204	6.78×10^{-4}	3.172	7.57×10^{-4}
20	3.434	2.97×10^{-4}	3.401	3.35×10^{-4}	3.371	3.74×10^{-4}		
30	3.512	2.22×10^{-4}	3.483	2.48×10^{-4}				
40	3.561	1.85×10^{-4}						

(2) Utility loss: The failure probabilities can be defined as utility loss, i.e., the functional defects or aging of bridges. In the past 10 years, 596 bridges have been demolished and rebuilt in the United States because of excessive car loading, which yields a failure probability of 10^{-4}[31]. As most bridge failures are caused by extreme events such as floods, fires, or earthquakes, which destroy many bridges that were functioning well, the failure probability of the bridge is between 10^{-4} and 10^{-5}.

3.4 Summary

In this chapter, we identified the five components for New Jersey Food supply chain which are suppliers, transportation, manufacturers, distribution centers, and retailers, and built a configuration of the New Jersey food supply chain network by creating a connection matrix which consists of distance and influence factors. The values in the connection matrix represent the probability of linkages connecting each pair of components. Then we defined the major type of risks and failure probabilities for each risk. In Chapter 4 we will further investigate the dynamics of the supply chain network.

CHAPTER 4

Risk Propagation Model

In a food supply chain, the risk occurring on one node may propagate to other nodes that are or are not directly connected to that node. This is also known as the ripple effect. Consequently, the impacted area of a risk would increase as time goes by, but the impact would eventually vanish when the company manages the risk and recovers from the disruption. These characteristics of supply chain risk propagation is similar to the propagation of virus in the biology domain. Our proposed model is motivated by the virus propagation model from biology. In Section 4.1, we review the virus propagation model; In Section 4.2, we propose a model for risk propagation in the New Jersey food supply chain.

4.1 Review of Virus Propagation Model

As reviewed in Chapter 2, models for virus propagation in the biology field may be adopted to analyze risk propagation in a supply chain. Risk diffusion in the supply chain network is very similar to the diffusion behavior of virus. This similarity makes the diffusion behavior of propagation dynamics model applicable for the risk propagation in supply chain network. One of the commonly used virus dissemination models is called “SIR”, where the three letters represent three different states of an individual: S (Susceptible), I (Infected), and R (Recovered). The SIR model was first proposed by Kermack and McKendrick [32] to describe the virus propagation in biology field.

In the SIR virus propagation model, individuals can be divided into three categories: Susceptible, Infected, and Recovered. Susceptible individuals will be infected with a certain probability after contacting infected individuals. Once infected, their state will change from healthy to infected. After being infected for a period of time, infected individuals will be cured at a certain rate and recover from infection. Recovered individuals will have permanent immunity and no longer spread virus.

Let the probability that a susceptible individual is infected by an infected individual within a certain time be α; and the recovery rate of an infected individual transiting to immune be β. The proportions of susceptible individual, infected individual, and recovered individual in the population are denoted by s, i, and r, respectively. So, virus propagation in SIR can be described by the following differential equations:

$$\begin{cases} \frac{ds}{dt} = -\alpha is \\ \frac{di}{dt} = \alpha is - \beta i \\ \frac{dr}{dt} = \beta i \end{cases} \tag{4.1}$$

The classical SIR propagation model described by differential equations is based on uniform network and can model the main features of virus propagation in the real world. However, it is not applicable to supply chain risk propagation due to the following limitations.

First, the SIR model assumes that all nodes are uniform. It assumes that all nodes have identical probabilities to be infected, and identical failure probabilities when facing a risk. However, this is not the case in the NJ food chain model, where every node has its own characteristics. For example, different nodes in supply chain may respond differently to the same risk according to their different risk resistance capabilities. For instance, when serious financial crisis occurs, big companies that have huge capital and well-prepared strategies can overcome the difficulty but small companies may go bankrupt very quickly. These small companies may be influenced by the risks with a higher probability. This is different from virus propagation where it assumes all nodes have the same response to the same risk.

Second, the SIR model assumes that one will spread the virus once it is infected. However, in supply chain there are some affected members who may not spread out the risks. After dealing with the risks for periods of time, those companies may solve the problem and will not disseminate the risks.

Last but not least, even if some members in supply chain can recover from certain risks after a period of time, they may not keep immune forever and may spread the risks again. The nodes may be influenced by multiple simultaneous risks even if the nodes can resist the risks when they occur individually. For example, a big manufacturer that can afford the financial risks coming from a couple of DCs might be affected again if more related DCs have financial problems at the same time. This is different from virus propagation where the recovered node will be immune from the virus forever.

4.2 The Proposed HNDR Risk Propagation Model

Due to the above limitations, a new model named HNDR is proposed based on SIR. In our proposed model, the nodes in the network are divided into four states: healthy (H), non-disseminating (N), disseminating (D), and recovered (R).

Healthy nodes are the companies that have not been exposed to risks yet and may change to another status as situations evolve. Disseminating nodes are the companies that are inclined to be impacted by risks and tend to propagate the risks. Non-disseminating nodes refer to the companies who are influenced by risks but do not disseminate the risks. Recovered nodes represent the companies which get recovered from the risks.

In order to more realistically represent the risk propagation in food supply chain network. our proposed model is able to describe the following situations:

- One impacted node in supply chain network can disseminate risk to all its connected nodes.
- Different nodes will be impacted by the same risk with different probabilities.
- Recovered nodes may spread the risks under multiple simultaneous risks.

The assumptions of the model are as follows. At each time unit:

- The probability that a disseminating (D) node *i* contacts a healthy (H) node *j* is equal to their connection probability c_{ij} calculated in Chapter 3.
- An H node *i* can become a non-disseminating (N) node with the following two situations: (1) it can evolve to an *N* node by itself with probability p_{1a}^{i}, or (2) when contacted by one or more D nodes, the H node becomes an N node with a probability p_{1b}^{i}. For simplicity, it is assumed that $p_{1a}^{i} = p_{1b}^{i} = p_i$, where p_i is the failure probability calculated in Chapter 3.
- An N node *i* transfers to a D node and an R node with probabilities p_2^i and p_3^i, respectively.
- A D node *i* transfers to a recovered (R) node with a probability p_4^i.
- An R node transfers to an N node when the percentage of the disseminating nodes in the entire network reaches or exceeds w percent. Define $\alpha(w)$ as a binary indicator that is equal to 1 if and only if the number of connected disseminating nodes reaches or exceeds w percent.

Based on these assumptions, the dynamics of the system can be represented by a discrete-time Markov chain, where the transition between different states is shown in Figure 4.1.

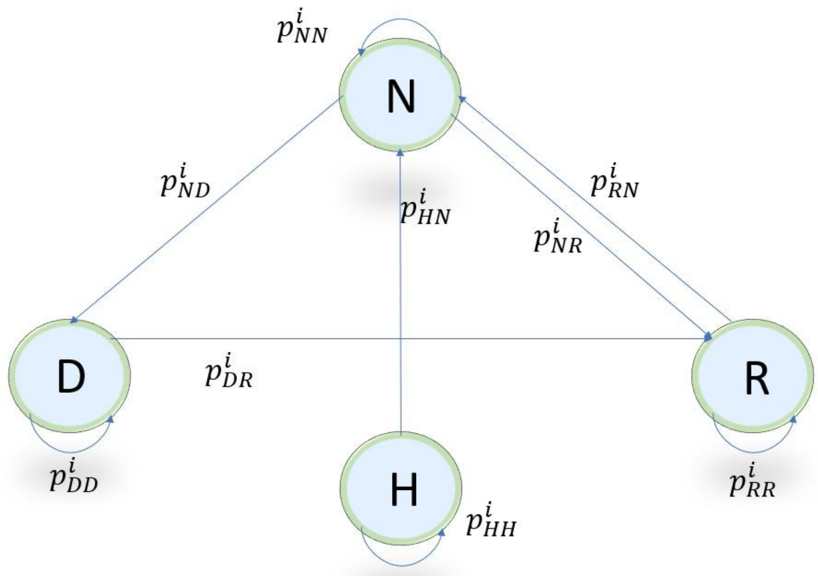


Figure 4.1 States and transition

Let p_{mn}^i be the probability that node *i* transfers to state *n* given an original state *m*, where *m*, *n* ∈ {H, N, D, R}. According to the above assumptions, p_{mn}^i can be calculated as follows:

$$p_{HN}^i = p_1 + \left[1 - \prod_{j\in D}(1 - c_{ji})\right](1 - p_1^i) \tag{4.2}$$

$$p_{HH}^i = \prod_{j\in D}\left(1 - c_{ji}\right)(1 - p_1^i) \tag{4.3}$$

$$p_{ND}^i = p_2^i \tag{4.4}$$

$$p_{NR}^i = p_3^i \tag{4.5}$$

$$p_{NN}^i = 1 - p_2^i - p_3^i \tag{4.6}$$

$$p_{DR}^i = p_4^i \tag{4.7}$$

$$p_{DD}^i = 1 - \ p_4^i \tag{4.8}$$

$$p_{RN}^{i} = \alpha^{i}(w) \tag{4.9}$$

$$p_{RR}^{i} = 1 - \alpha^{i}(w) \tag{4.10}$$

All the transition probabilities that are not listed in Equations (4.2) to (4.10) are equal to zero.

In Equations (4.2) and (4.3), $\left[1 - \prod_{j \in D}(1 - c_{ji})\right]$ represents the probability that an H node i is contacted by one or more D nodes, and the "D" in these equations represents the set of D nodes.

4.3 Risk Propagation in Simulation

Based on the transition probabilities established above, theoretically one can build an a discrete-time Markov Chain model to analyze the risk propagation in the supply chain. However, in our problem, since there are 293 nodes with four states for each in the network, the total possible combination of states is 4^{293}, making an analytical solution practically infeasible. Therefore, simulation is used to implement the risk propagation model.

The pseudo-code of the simulation algorithm is illustrated as follows:

```
Initialize the number of nodes N, the number of risks Q, the total time steps T, and number
of replications R.

  For q = 1: Q
       Generate random numbers for  p^i_DR, p^i_ND, p^i_NR
       Load p^i_HN
       for r =1:R
           Initialize S_i(0) = 'H' for i = 1,…,N
           for t = 1: T
               If  S_i(t – 1)='H' and p^iq_HN > random(0,1)
                   S_i(t)='N'
               elseif S_i(t – 1)='N' and p^i_ND > random(0,1)
                   S_i(t) ='D'
               elseif S_i(t – 1)='N' and p^i_NR > random(0,1–p^i_ND)
                   S_i(t)='R'
               elseif S_i(t – 1)='D' and p^i_DR > random(0,1)
                   S_i(t)='R'
```

```
                    elseif S_i(t – 1)='R' and the number of D nodes/N >= p_RN^i
                        S_i(t) ='N'
                    end
               for i = 1: N
                         if S_i(t – 1) = 'D'
                              for j = 1: N
                                   if  c_ij > random (0,1) % nodes i and j are connected
                                        if S_j(t – 1)='H' and p_HN^jq >0
                                        S_j(t)='N'
                                    end
                                 end
                            end
                       end
                 end
            end
      end
```

This algorithm considers two types of transitions among states: (1) the transitions among H, N, D, R states based on Figure 4.1, (2) an H node can become an N node if contacted by a D node.

4.4 Summary

In this chapter, we first introduced SIR model and discussed its applicability in supply chain network. Based on the SIR model and the unique characters of supply chain, we proposed an HNDR model where each node has Healthy, Non-disseminating, Disseminating, and Recovered states. The transitions among these states are also analyzed. Simulation is used to implement the proposed model. The application of this model will be illustrated in case studies in the next chapter.

CHAPTER 5

Simulation and Results

In this chapter, we apply the proposed HNDR model in simulations to analyze the critical assets in the network. In order to simplify the introduction and test the effectiveness of the proposed model, we first select 5 nodes from the network as a simple case study to illustrate the HNDR model and the risk propagation mechanism. Then the simulation method is applied in the entire New Jersey food supply chain network to find out the most critical assets.

5.1 Case Study in a Small Network

As an illustration of the proposed method, we create a simulation model in a small network with 5 nodes from the five independent sections–Supplier, Manufacturer, Distribution Center, Retailer and Transportation. The selected nodes are shown in Table 5.1.

Table 5.1 Five nodes network

Names	Sections	Longitude	Latitude
Cherry Grove Farm	Supplier	40.3083691	-74.712445
I78	Transportation	40.6074316	-75.298813
Givaudan	Manufacturer	40.8159204	-74.34165
International Food & Liquor Warehouse	Distribution Center	40.887991	-74.067969
Walmart (Saddle Brook)	Retailer	40.8922932	-74.093783

The drivers of supply chain risks are summarized in Figure 5.1. According to the Top 3 supply chain risk drivers in the recent 5 years [33], we use the most representative drivers to simulate the performance as in the example. These critical supply chain risk drivers can simulate the most frequent cases. In this case study, we choose quality issue as the regional risk which would spread out and influence nearly all the elements in the whole network.

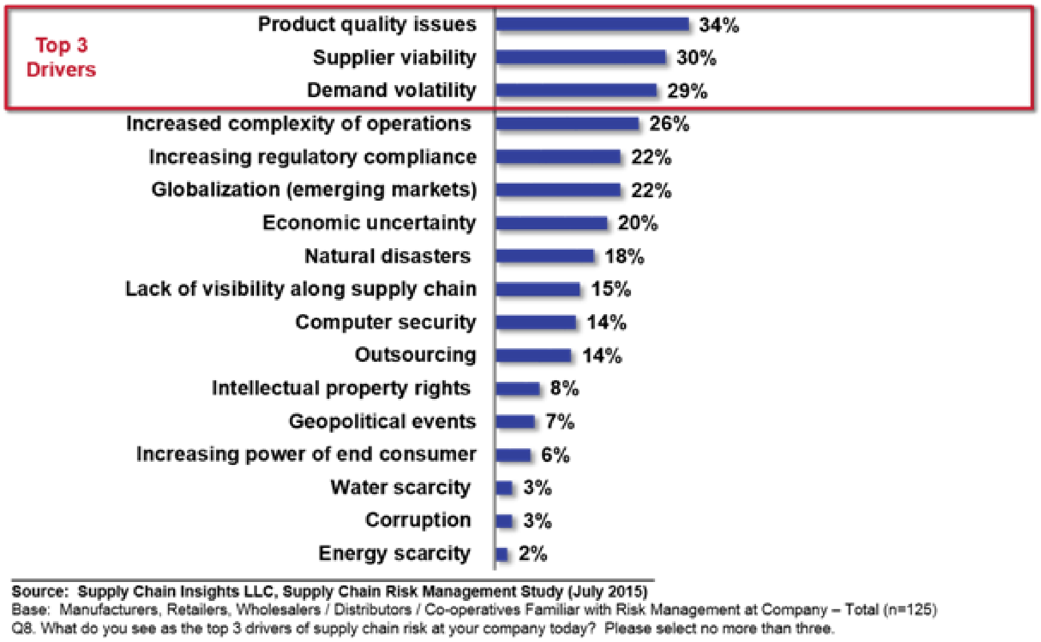
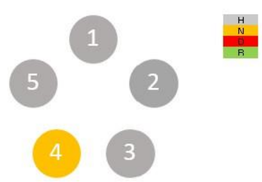
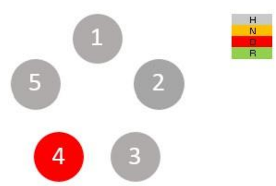
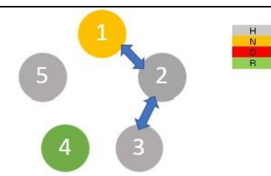
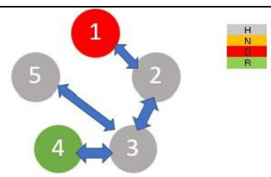
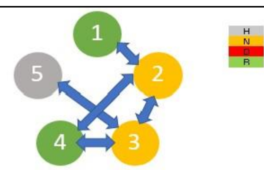
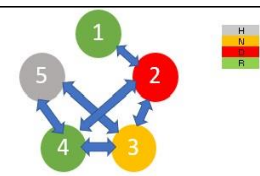
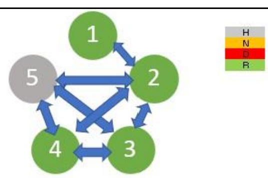
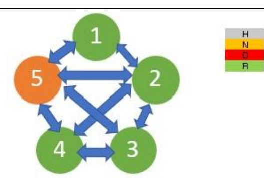
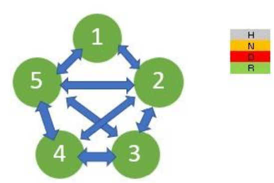


Figure 5.1 Top 3 drivers of supply chain risk [33]

5.1.1 Illustration of the Model in the Small Network

One sample path is generated in simulation to illustrate the HNDR model. In this example, 1,2,3,4 and 5 represent Supplier, Manufacturer, DC, Retailer, and Transportation, respectively. In each step, the states of all nodes are recorded. The simulation was conducted for 50 steps, while changes occur in only 9 steps. These steps are shown in Table 5.2. At step 0, all the nodes are set as H. That is, all the members in the network are in healthy state. After we apply a regional risk in step 1, all nodes are potentially affected. A risk occurs at node 4 and its state becomes N from H at step 3. Then node 1 is affected and becomes disseminating at step 4. At step 5, node 4 gets recovered but node 1 becomes infected but non-disseminating. When node 1 deteriorates to disseminating at step 7, the risk may spread out along its connecting nodes. At step 17, the risk spreads to node 2 which then becomes non-disseminating but node 1 gets recovered; at the same time, node 3 transits from H to N. At step 19, node 2 recovers from the risk and keeps unchanged since then. Node 5 becomes non-disseminating at step 36 but gets recovered very soon at step 38. There are no changes after step 38. This is because the affected companies have recovered from the risk.

Table 5.2 Risk propagation steps breakdown

Step 3	Step 4	Step 5
		
Step 7	Step 17	Step 18
		
Step 19	Step 36	Step 38
		

5.1.2 Risks Evaluation in the Small Network

Next, we evaluate the degree of the risk on different types of nodes, which is measured by the total number of nodes that are in the states of D and N in the entire process. 50 replications of the simulation were run. The numbers are scaled to the range between 0 and 10. The result is shown in Table 5.3, where a larger number represents a more serious risk.

Table 5.3 Risk seriousness for the 8 scenarios

	Supplier	Transportation	Manufacturer	Distributor	Retailer
Management risk	2	1	5	1	6
Financial risk	3	0	4	1	3
Technology risk	0	0	7	0	2
Quality risk	2	0	5	1	4
Logistic risk	2	4	5	5	7
Market risk	2	0	10	2	6
Natural risk	5	4	2	2	4
Societal risk	2	5	5	3	7

The impact of the eight risks on each of the five nodes is demonstrated in the following radar charts:

Figure 5.2 Supplier risk

Figure 5.2 shows the potential threats to the suppliers when the specific risk is applied. A higher value indicates a more serious consequence. Based on the result, the supplier's vulnerabilities and resiliencies are analyzed as follows:

Supplier's vulnerabilities:

Natural risk = 5. The weather and natural disasters most seriously impact the agriculture and the food suppliers. The yield rate of the crops would consequently impact others significantly.

Financial risk = 4. The farm owners are also seriously impacted by the cash flow disruption. As most of them are self-employed and can be easily short of money.

Management risk = 3. Most of the food suppliers are small farms that don't have effective management systems.

Quality risk = 3. The quality issue of food products (fruit and vegetable crops) is a major concern for the suppliers. An example is the E. coli problem of Arizona lettuce in 2018 that led 5 people dead and nearly 200 sickened, let alone the huge amount of money spent on recalling the lettuce [34].

Supplier's resiliencies:

Technology risk = 0. The traditional agriculture would not be influenced so much by technology.

Societal risk = 2. Societal risks seldom affect the food suppliers, as they are mostly self-employed and always can ensure the sufficient outputs in case of any social issues.

Market risk = 2. The supplier is not always influenced by the market as the demands for food are relatively stable. People would not change their preference on food, so the supplier can plan their cultivation and the stable yield would not influence the market.

Logistic risk = 2. The supplier is not easily constrained by the logistic risks, as it can regularly ship out the products to the manufacturers.

Similarly, one can analyze the risk on the other parties in the supply chain (i.e., manufacturer, distribution center, retailer, and transportation), as summarized from Table 5.4 to Table 5.7, respectively.

Table 5.4 Manufacturer's vulnerabilities and resiliencies

 	**Market Risk = 10** The manufacturer is extremely influenced by the market demand fluctuation. **Technology Risk = 7** High technology could bring in more money to the company or even determine its future destiny. **Management Risk = 5** Companies would deteriorate very quickly without good management system. **Quality Risk = 5** The quality issue of one manufacturer would ruin its reputation and may evoke further large issue as the other risks. **Financial Risk =5** Account receivable and account payable which would block cash flow are the headaches to each company. **Logistic Risk =5** The factory replies on logistic to get the raw materials from the suppliers and ship out the products to DC.
	Natural Risk = 2 The manufacturer has plant and warehouse which are seldom influenced by the weather or natural disaster.

Table 5.5 Distribution center's vulnerabilities and resiliencies

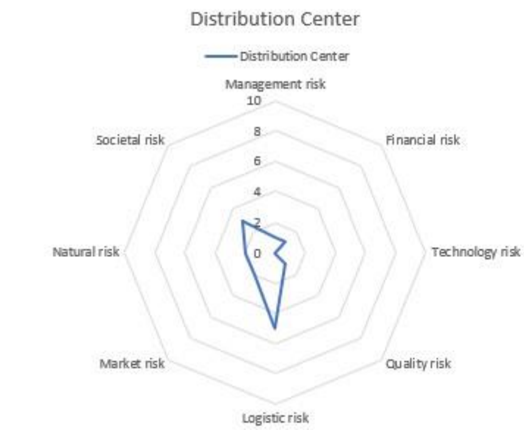
<table>
<tr>
<td rowspan="2">
</td>
<td>Logistic Risk = 5
Logistic is the main business of DC. It provides services of storages and deliveries for the retailers.</td>
</tr>
<tr>
<td>Technology Risk = 0
DC also does not need frequent technology upgrades.
Quality Risk =1
Since DC does not have production, good storage condition can ensure high quality of product.
Financial Risk =1
DC does not need great cash flow to keep the business running.
Management Risk =1
DC has to regularly maintain warehouses and facilities which is related to management risk.</td>
</tr>
</table>

Table 5.6 Retailer's vulnerabilities and resiliencies

<table>
<tr>
<td rowspan="2">
</td>
<td>Market Risk = 6
The retailer has direct connection with the end customers. So, it is the first to be impacted by the demand fluctuation.
Management Risk = 6
Like the manufacturer, the retailer also needs great management system to keep smoothly running.
Logistic Risk = 7
Storages and deliveries are also needed by the retailer. Any risk coming from logistic would influence its business.
Societal Risk = 7
Any societal risk such as labor strike may cause shutdown of retailer's business.</td>
</tr>
<tr>
<td>Technology risk = 2
Technology upgrade is not critical to the retailer, as retailer does not request frequent information or technology update.</td>
</tr>
</table>

Table 5.7 Transportation’s vulnerabilities and resiliencies

<table>
<tr>
<td rowspan="2">
</td>
<td>Logistic Risk = 4
All the nodes need transportation to be connected with each other. Any logistic risk would influence the whole network.
Societal Risk =5
Although societal risks such as labor strike or terrorist attack seldom
happen, their impacts on the supply chain are huge.
Natural Risk =4
Natural disaster such as flood or blizzard would disrupt the traffic and weaken the supply chain.</td>
</tr>
<tr>
<td>Management risk =1, Financial risk =0, Technology risk =0, market risk =0, Quality risk = 0
Transportation is a special node in the network. It is barely influenced by the risks which the other elements may have, such as financial, market risks, etc.</td>
</tr>
</table>

5.2 New Jersey Supply Chain Risk Simulation

Next, we apply the same methods to model the risk propagation in the entire NJ food supply chain which consists of 293 nodes. A 300 time-step simulation was conducted with 50 replications. The main simulation is performed with MATLAB, followed by two VBA programs for matrix calculation and Python programs for risk mitigation analysis.

5.2.1 Risk Propagation Process in NJ Food Supply Chain Network

Eight risks are analyzed in the network. As an example, Figure 5.3 shows how the numbers of the four states (i.e., H, N, D, R) change during 300 steps when the management risk was applied. It can be seen that, in the beginning, the number of healthy nodes decreases dramatically while the numbers of non-disseminating, disseminating and recovered nodes increase. This implies that when a risk first occurs, companies close to the risk source are affected. Few of these companies may have strong risk management capabilities, so they become non-disseminating or even spread out the risk. Starting from approximately step 10, the numbers of the states change gradually, and eventually reach a stable value around step 210. The reason is that some companies can prepare for the risk or recover from the risk and become immune. From step 210, the majority of companies have settled down in either H or R state. The simulation results agree with the real situation in the supply chain: When a sudden risk appears, it will impact the closer companies and disseminate in the network. After a period of time, most companies can get recovered because of their strategies of risk management.

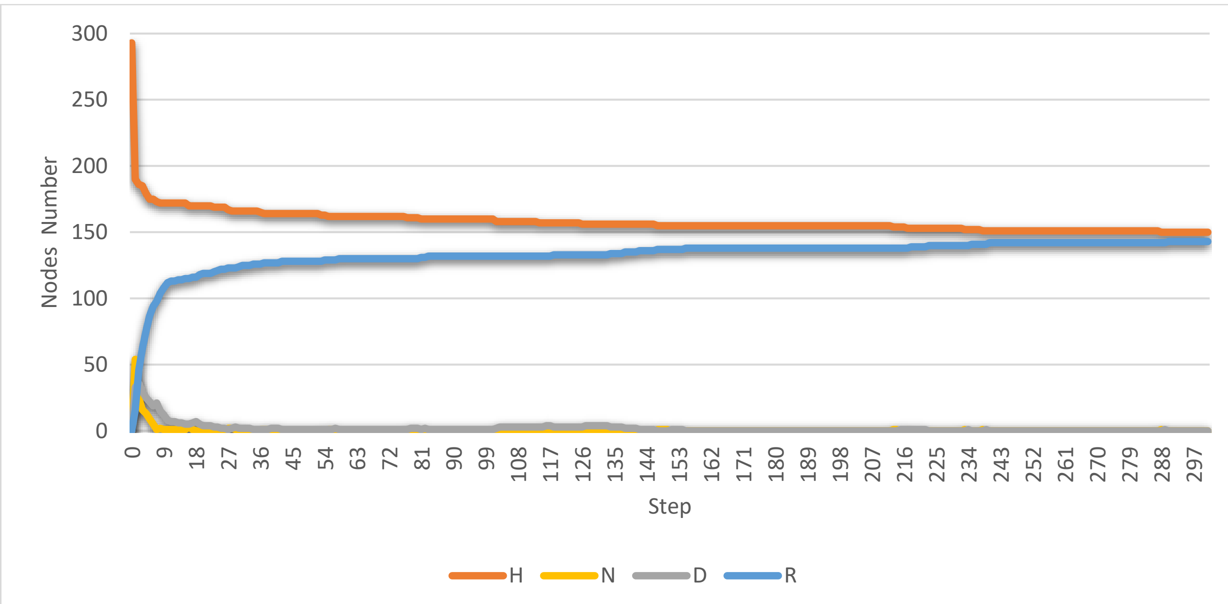


Figure 5.3 The number of H, N, D, R nodes over time

5.2.2 Risk Propagation Results

After applying the 8 risks for each node, we took the average of the results to find out the nodes that may be seriously impacted in the whole supply chain. These critical assets are summarized in Table 5.8.

Table 5.8 Summary of the simulation result

Supply Chain Component	Node Index	Asset Name
Impacted the most	223	Bai Brands
Impacted the least	67	I295
Impacted the most among suppliers	19	Farmstead Estate
Impacted the most among transportation	191	R44
Impacted the most among manufacturers	223	Bai Brands
Impacted the most among DCs	259	Haines Industrial Center
Impacted the most among retailers	283	Walmart Edison

In the entire network, Bai Brands, a manufacturer located in Trenton, would experience the greatest impact facing risks. The reason may be that as a manufacturer, Bai Brands has more chances to be exposed to the risks. I295, which is a transportation node, would experience the smallest impact in the network when we induce the risks. Transportation nodes are barely influenced by the market risk, technology risk, or financial risk.

Among all suppliers, Farmstead Estate would be affected most when risks are induced. For transportation, R44 would suffer the greatest impact. When looking into specific data such as geographic position, it is found that this road locates along the river bank to Philadelphia. Furthermore, Haines Industrial Center and Walmart Edison are the most critical warehouse and retailer, respectively.

5.2.3 Heatmaps of NJ Supply Chain Risk Propagation

In order to visualize the risk degree of all the nodes in the network, Python with Google Map API is used to generate the heatmaps to illustrate the risk level of each node in the New Jersey food supply chain, as shown in Figure 5.4, where green, yellow, and red represent low, medium and high-risk consequences, respectively.

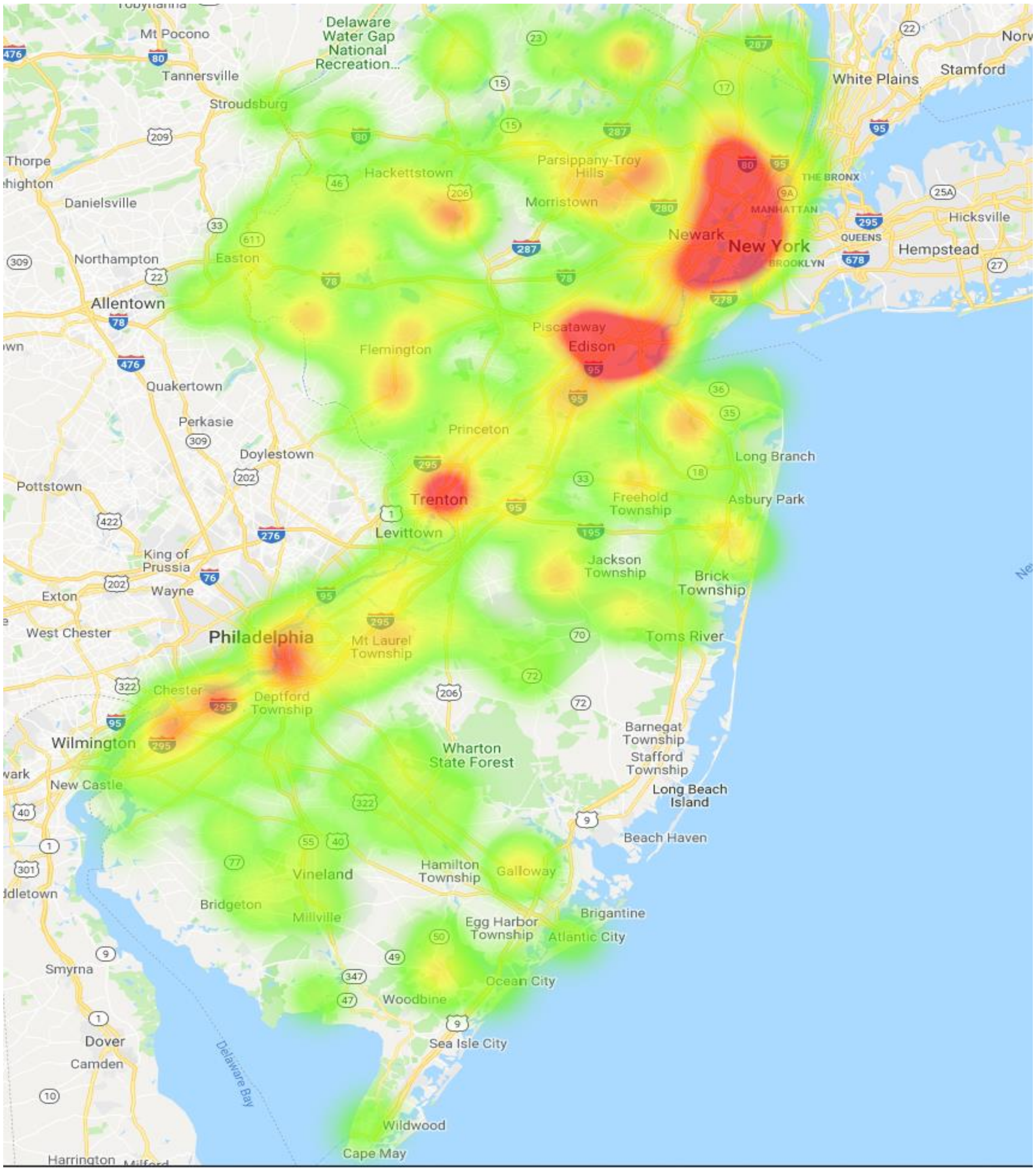


Figure 5.4 Heatmap of NJ food supply chain critical nodes

This map reveals that the risks are more likely to occur in more populated and metropolitan areas. For example, the areas around New York City and Philadelphia have more red spots than any other region. It agrees with one’s intuition as companies are more likely to establish their business in the area where there are more opportunities and more residents to be served, especially for food. Another observation is that more companies are inclined to set up their business in cities along the river bank, where companies can take advantage of water transportation, railway, inter-state roads or other infrastructure. Figures 5.5(a) and (b) show that although there are many facilities distributed in the different regions of NJ, most high-risk ones are around New Year City and Philadelphia.

Figure 5.5 (a) Heatmap of southern NJ food supply chain

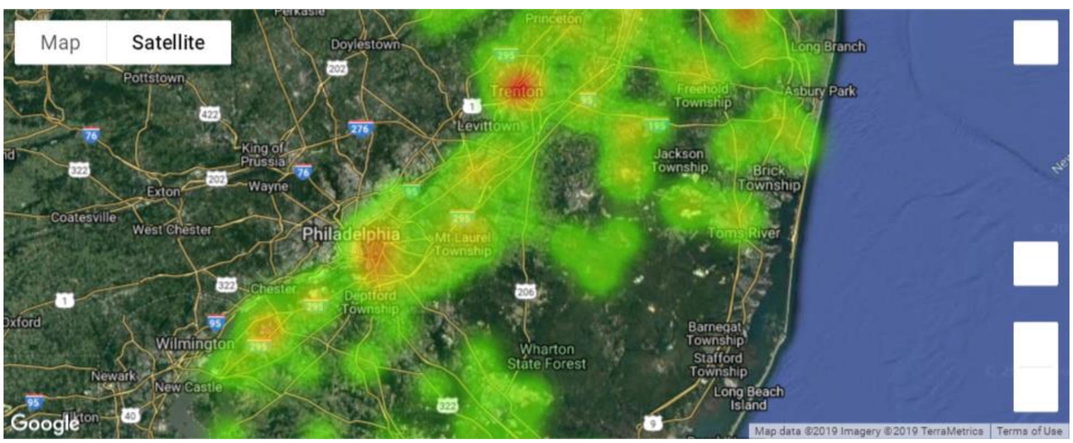


Figure 5.5 (b) Heatmap of western NJ food supply chain

5.3 Risk Mitigation

In this section, we study the strategies to mitigate the risks. First, clusters are created according to K-means clustering [35]. Then, based on the clustering result, some risk mitigation strategies are proposed.

5.3.1 Clustering of Nodes

Python 3.7 and Jupyter notebook were used to create the clusters for the nodes in the entire network. For each node, the following attributes are used for clustering: (a) location (i.e., longitude and latitude), (b) node type (i.e., supplier, transportation, manufacturer, distribution center, or retailer), (c) risk degree (as calculated in Chapter 5.2), and (d) top risk (among the eight risks mentioned above).

First, the data need to be preprocessed as they have different types of attributes. Their location and risk number are scaled to the range of 0 to 1. Node type and top risk are categorical so they are transferred to binary by one-hot encoding. After preprocessing, there are total 14 attributes.

Next, the optimal number of clusters needs to be determined. Figure 5.6 shows the relationship between the sum of squared distances and the number of clusters *k*. According to Elbow method [36], the steep curve in Figure 5.6 becomes flat when *k* is 3, which is selected as the optimal number of clusters.

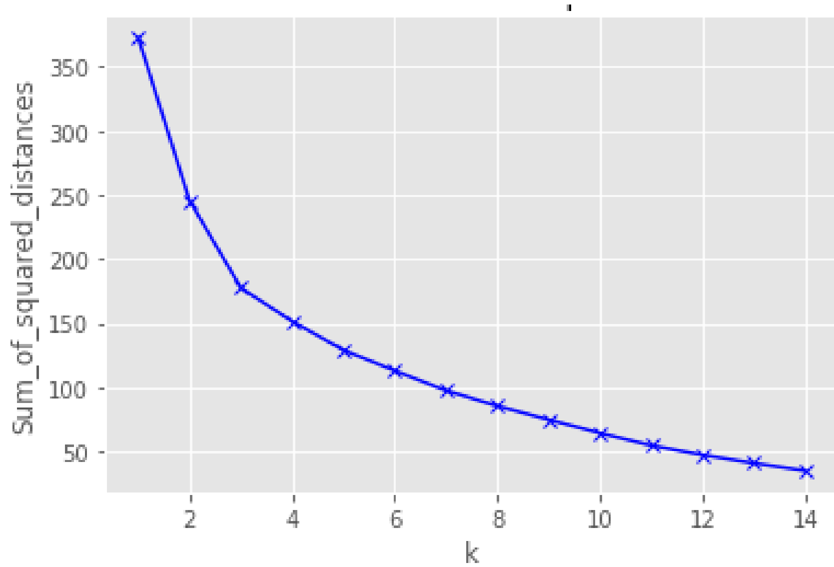


Figure 5.6 Elbow method for the optimal k

Then, all nodes are assigned to one of the three clusters. Figure 5.7 shows the geographic location for the nodes with their individual cluster in Leaflet map (different clusters are represented by different colors). The clusters are scattered distributed on the map because they are selected according to multiple attributes other than the location alone.

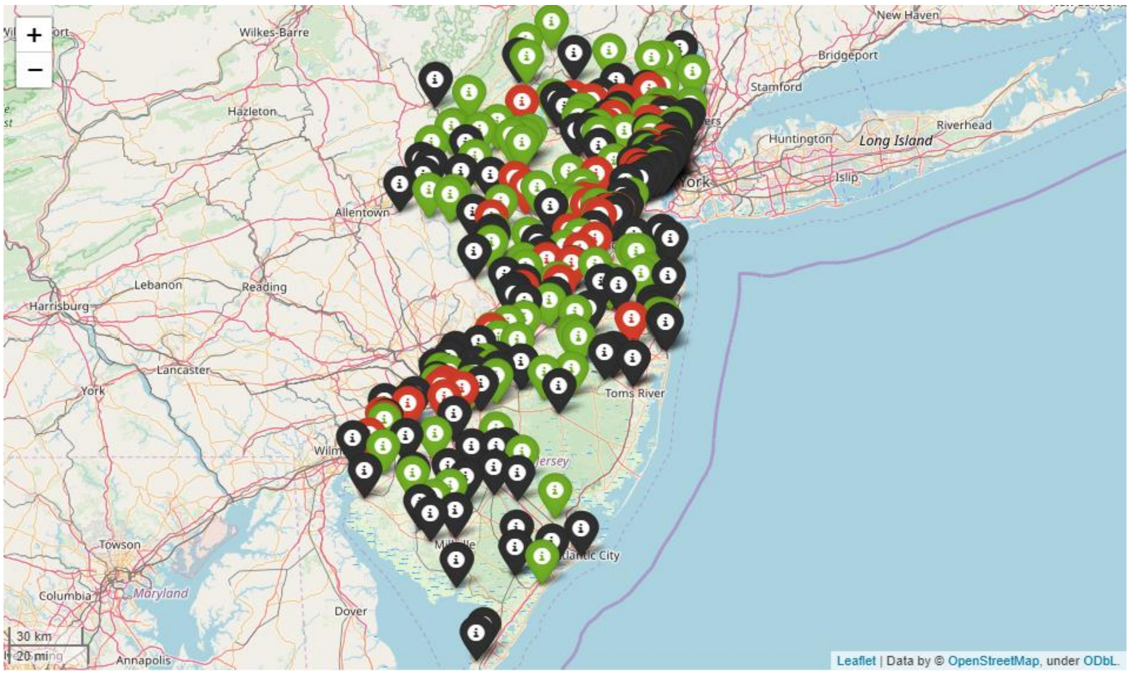


Figure 5.7 K-means clustering for NJ food supply chain

5.3.2 Risk Analysis and Proposed Mitigation Methods

It is recommended to select cluster 2 (i.e., the red nodes in Figure 5.7) as the top priority of the potential risks to be removed, because this cluster has high risk degrees of 7 to 10. This cluster is in the areas where there are more business opportunities, and it consists of 71 commercial organizations (i.e., suppliers, manufactures, DCs, and retailers) located around big cities. Their top risk is market risk. Compared with the other risks, this kind of high potential risk is relatively easy to control. For example, the manufacturers can develop advanced analytics tools to more accurately predict the market demand and to better adapt to the market changes.

The second priority will be given to cluster 0 (i.e., the green nodes in Figure 5.7), which consists of majority of suppliers and some manufactures, DCs, and retailers. There are 74 nodes in this cluster, whose risk degrees are around 2-3 and the top risk is natural disaster. Although it is difficult to control the weather, strategies can be developed to mitigate its influence. These strategies include: (1) Early warnings. The provision of timely information enables the suppliers and transportation department to take steps to reduce the impact of hazards [37]. (2) Disaster mitigation. For example, more shelters can be built to reduce the risk caused by tornado. (3) Loss prevention. The government can also help raise public awareness and preparedness through training or education projects.

The final cluster consisting of the 148 transportation nodes (shown as the black nodes in Figure 5.7) has the lowest potential risks whose degree is in the range of 0 to 2. At most of time, majority of the transportation infrastructure in the network could work properly without any major problem. The top risk is still natural disaster, so the similar risk mitigation strategies as we mentioned above can be adopted, such as monitoring the health of transportation infrastructure and doing regular or preventive maintenance.

5.4 Summary

To demonstrate the effectiveness of the proposed HNDR and the risk propagation mechanism, a simulation for a 5-node network was first performed in this chapter. Then the simulation for the entire network of the New Jersey food supply chain was conducted to find out the critical assets. Based on the result, a heatmap was generated to illustrate the risk degree of each node. These nodes were further split to three clusters and risk mitigation strategies were proposed based on the clustering result.

CHAPTER 6

Summary and Future Work

6.1 Summary

The food industry in New Jersey is massive and thriving, and its supply chain is vulnerable because a single disruption to one element could spread out and bring huge impact to the entire system. This ripple effect may have a tremendous impact on not only the state's economy and job market, but also the state's security, vulnerability, and resiliency. Food supply chain risks may occur naturally, intentionally, or accidentally. No matter how a risk originates, it may propagate along the connected members and then impact the entire network.

This thesis aims to study the risks in New Jersey food supply chain. The thesis first introduces the current status of New Jersey food supply chain and then reviews the existing studies on supply chain risk modeling and propagation. To identify the critical assets in New Jersey food supply chain, the important nodes, as well as their connection probabilities and failure probabilities are defined. New Jersey food supply chain is then configured with 293 nodes and 8 regional risks. A new model for risk propagation is developed based on the traditional virus propagation models. The proposed risk propagation model is then implemented in simulation for New Jersey food supply chain network. Simulation results demonstrate how risks propagate through the network and which assets are impacted the most in the food supply chain. At last, these nodes are divided into three clusters and some risk mitigation methods are proposed.

This research is timely to identify the risks and analyze their impacts to the NJ food supply chain. Understanding how risks propagate through the network will provide us with important insights into vulnerability assessment for the critical assets in New Jersey food supply chain. Based on the risk analysis and propagation in this thesis, risk mitigation plans and preparation strategies can be further developed.

6.2 Future Work

The model and analysis in this thesis can be extended in the following aspects:

(a) Evaluation of the effects of risk mitigation strategies and their effects. Based on the model developed in this thesis, one could quantitatively analyze the effect of different risk prevention or mitigation strategies, evaluating their impact on the supply chain performance.

(b) Consideration of detailed risks. Eight types of risks are considered in this thesis. These risks can be further divided into more detailed levels. For example, one could classify the natural disasters into heavy rain, blizzard, flood, hurricane, etc., and for each different type, more specific mitigation strategies can be developed.

(c) Integration of NJ food supply chain and external networks. This thesis only focuses on the components inside the New Jersey food supply chain. But in real life, the NJ food supply chain is also influenced by external factors (e.g., the supply chain in New York). These external factors and their interactions with the NJ food supply chain can be considered in the future.

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