SUPPLY CHAIN NETWORK DISTRUPTIONS AND EXPECTED RISK EXPOSURE

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ABSTRACT

SUPPLY CHAIN NETWORK DISTRUPTIONS AND EXPECTED RISK EXPOSURE

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Logistics Management Graduate Program, Graduate School of Social Sciences

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With globalization, supply chain network disruptions are becoming more and more important. Companies are in continuous effort trying to minimize its effects. In this thesis, supply chain disruptions are evaluated in the context of network models by using mathematical programming approach. Supply chain risks may occur in different times due to different factors affecting different functions. Considering the geographical locations of supply chain members, important part of supply chain disruptions is caused by natural disasters. Nevertheless, companies should be aware of their expected risk exposure for their supply chain networks and try to minimize it. In this study, expected risk exposure calculation and optimal facility location decisions are integrated and analyzed with disruption risks considering the given disruption scenarios. Three mixed integer programming models are developed and solved. Numerical examples are given to justify the usefulness of the proposed models and calculate the expected risk exposure values.

Keywords: Supply chain network, facility location, disruption, expected risk exposure

ÖZET

TEDARİK ZİNCİRİ AĞINDAKİ AKSAMALAR VE BEKLENEN RİSK TUTARI

Özdağ Özkan, Gül

Lojistik Yönetimi Yüksek Lisans, Sosyal Bilimler Enstitüsü

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Küreselleşmeyle birlikte tedarik zinciri ağlarında oluşan aksamaların önemi giderek artmaktadır. Firmalar her zaman bu riskin etkilerini en aza indirgemeye çalışmışlardır. Bu tezde aksama, tedarik zinciri ağı modellerinde matematik programlama yaklaşımları kullanılarak incelenmiştir. Riskler işleyişi etkileyen farklı zamanlarda, farklı etkenler sayesinde ortaya çıkarlar. Tedarik zinciri elemanlarının coğrafik yerleşimleri göz önüne alındığında, aksamalardaki önemli kısım doğal afetler tarafından kaynaklandığı anlaşılmaktadır. Bununla beraber, firmalar tedarik zinciri ağlarındaki beklenen risk tutarı değerlerinin farkında olmalı ve en aza indirgemelidirler. Bu çalışmada, beklenen risk tutarı ve yer seçimi kararları entegre olmuş ve analiz edilmiş, aksama riskleri verilen aksama senaryolarına göre düşünülmüştür. Üç adet karışık tamsayı programlama modeli oluşturulmuş ve çözülmüştür. Öne sürülen modellerin kullanışlı oluşunu doğrulamak için sayısal örnekler verilmiş, beklenen risk tutarları hesaplanmıştır.

Anahtar Kelimeler: Tedarik zinciri ağı, yer seçimi, aksama, beklenen risk tutarı

To my mother

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CHAPTER 1

INTRODUCTION

For the analysis of supply chain disruptions, one should start with the definition of supply chain. There exist several definitions of supply chain and supply chain management. In Insme research report [1], supply chain is defined as combined set of resources or processes starting from raw material and ending at final customer. According to this definition, indirect members such as vendors, distribution centers, and logistics service providers are considered as part of supply chain. Another definition by Ellram, Lambert and Stock [2, pp.3] is:

> "*A supply chain is the alignment of firms that bring products or services to market.*"

Ganeshan and Harrison [3, pp.1] also define supply chain as:

> *"A supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products and the distribution of these finished products to customers."*

Referring to Handbook of Supply Chain Management[1], it is described as:

> *"Supply chain: Product life cycle processes comprising physical, information, financial, and knowledge flows whose purpose is to satisfy enduser requirements with physical products and services from multiple, linked suppliers."*

1.1 SUPPLY CHAIN MEMBERS

According to Chopra and Meindl [4], supply chain members are quite diversified. Typical supply chain members are suppliers, manufactures, vendors, retailers, wholesalers, distributors, logistics firms, customs or insurance firms. They are called supply chain members since supply chain flow passes through these facilities. In traditional supply chains, suppliers are the initial members and end customers are the final members. In case of reverse flow of goods, supply chain members may be connected in cyclic formation. Every member effects the operation of the supply chain. Each member has different responsibility to provide supply chain for continuing its processes.

1.2 SUPPLY CHAIN STRUCTURES AND RESEARCH AREAS

Typically, each supply chain has information, cash, material or service flow. Flow has a property to connect supply chain members to each other and also to integrate the whole supply chain. Flow directions can be different. It can be constructed in one direction, both directions, or as a cycle.

[1] Handbook of Supply Chain Management

It can be observed that there exist diversified research areas while dealing with supply chains. These are analyzed under the umbrella of supply chain system. For effective and integrated supply chain operations, the concept of supply chain management should be well-defined.

Kersten et al. [5, pp.8] define *"supply chain management"* as follows:

> "*Supply chain management, is a concept which contains all strategies and measures, all knowledge, all institutions, all processes and all technologies, which can be used on the technical, personal and organizational level to reduce supply chain risk."*

An alternative definition is provided in APICS[2] dictionary:

> *"Supply chain management: The design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally."*

According to the Council of Supply Chain Management Professionals (CSCMP)[3],

> *"Supply chain management encompasses the planning and management of all activities involved in sourcing, procurement, conversion, and logistics management. Importantly, it also includes the crucial components of coordination and collaboration with channel partners, which can be suppliers*, intermediaries, third-party service providers, and customers."

Council of Supply Chain Management Professionals (CSCMP)[4] proposes a different definition for supply chain management.

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[2] APICS (Advancing Productivity, Innovations and Competitive Success)- The Association for Operations Management

[3] CSCMP Supply Chain Management Process Standards, http://cscmp.org/resources/standards.asp

"Supply chain management: The design, planning, execution, control, and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, leveraging worldwide logistics, synchronizing supply with demand, and measuring performance globally."

In essence, supply chain management integrates supply and demand management within and across companies. Supply chain management is the integration of key business processes across the supply chain for the purpose of adding value for customers and stakeholders (Lambert, 2008)[5].

1.3 SUPPLY CHAIN RISKS

As can be perceived, supply chain is very important for every company in all industries and all business areas. Ideally, supply chain dynamics and its mechanism should not be destroyed or collapsed. However, the real world conditions such as natural threats, terror commitments, natural disasters, economic crisis, governmental laws, war hazards, strikes or epidemic illnesses influence supply chain mechanisms negatively. In the study of Ji and Zhu [6], supply chain risks are specified as earthquakes, economic crises, epidemics, strikes and terrorist attacks. Risks are quite diversified, from natural disasters, to strikes, and even plan and control risks within a company.

Many authors in the literature intend to define supply chain risks. According to Xu [7, pp.3]:

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[4] CSCMP Supply Chain Management Process Standards, http://cscmp.org/resources/standards.asp

[5] Lambert, Douglas M. *Supply Chain Management: Processes, Partnerships, Performance*, 3rd edition, 2008.

“Risk is not only a common word but also a complex word with an unclear definition. Until now there was no consolidated theoretic definition of risk, but the popular explanations are mainly as follows: risk is

- *uncertainty of outcomes*
- *probability of lost or lost occurrence*
- *deviation of outcomes from expectation*
- *change leading to loss*
- *danger of harm loss.”*

Considering the study provided in [7], there are two aims for managing supply chain risks. The first is to perceive all potentially identified risks and the second is to enhance the capacity of the supply chain as much as possible by keeping the chain flexible and integrated.

Another study related to supply chain risks is due to Ya-feng and Qi-hua [8]. They use two-tuple fuzzy linguistic representation model for ranking and classifying supply chain risk factors. They separate risks into three groups, which are: risk averse, risk neutral and risk love. Risk averse group carries the lowest attitude coefficient of the decision maker towards the risk. Certainly, risk love group has the highest attitude coefficient. Their aim is to support firms towards supply chain risk management.

Ritchie and Zsidisin [9] express the risks in supply chain in terms of eight main concepts. These concepts are risk identification, risk modeling, risk analysis, assessment and impact measurement, risk management, risk monitoring and evaluation. From their book, detailed information can be gained about the risks in the supply chain.

Königs [10] adapted the risk map according to risk occurrence, risk impact and risk acceptance. The result this study enables efficient analysis and perception of risks. It can be seen below in Figure 1.

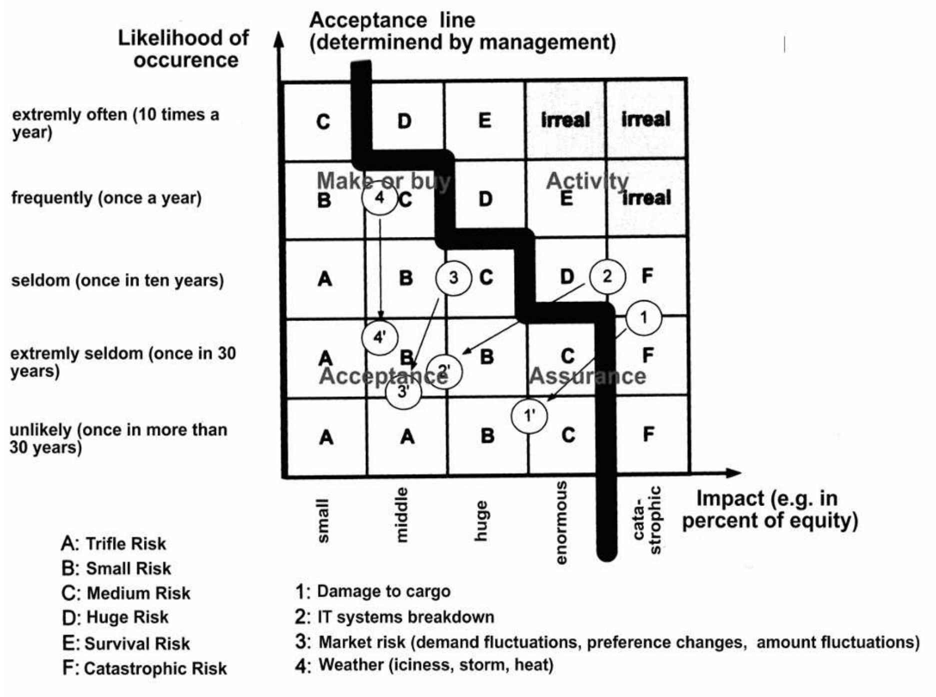

Figure 1. Risk map (Source: [10])

According to Teuteberg [11], risks can be grouped into five categories. The author divides risks as man made and natural risks. The author separates man-made risks within firm. First four categories related with man made risks and the last category is related with natural risks.

These categories are:

1. Plan and control risks (applied methods, concepts and tools etc.)
2. Supply risk (quality of material, global sourcing, damage to cargo, monopoly situations and supply market etc.)
3. Process risk (lead times, quality, machine damage, capacity bottleneck etc.)
4. Demand risk (demand fluctuations, planning and communication flaws in sales

inflexibility etc.)

5. Environmental risk (natural disasters, political instability, import or export controls, Social and cultural grievances etc.)

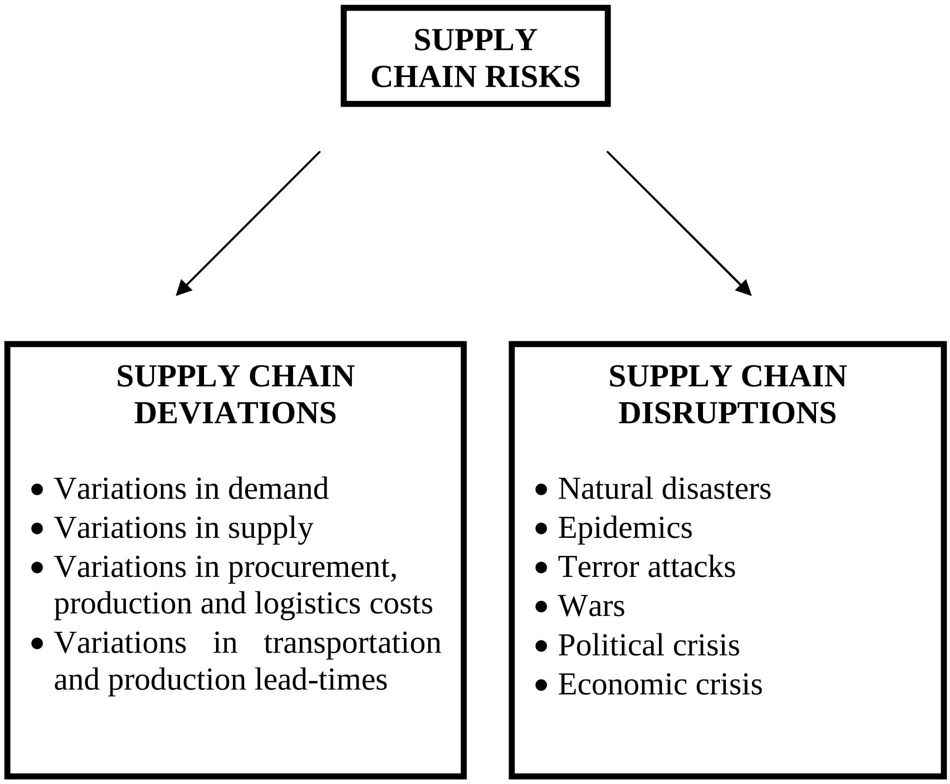

Figure 2. Difference between supply chain risks and supply chain disruption risks.

The difference between *“supply chain risks”* and *“supply chain disruptions”* is important to note. For this purpose, one can refer to Gaonkar and Viswanadham’s study in [12]. They point out that supply chain risks cover wide area as shown in Figure 2. Supply chain risks are divided into two main groups, supply chain deviations and supply chain disruptions. In this Thesis *“supply chain disruptions”* are evaluated.

1.4 SUPPLY CHAIN DISRUPTIONS

If one member or a connection of the supply chain is destroyed, the whole chain suffers. Therefore, analyzers should consider all members in order to protect supply chain from disruption. Supply chain disruptions result in extremely high costs. In this context, Rob Handfield, (Director, Supply Chain Resource Consortium, NC State University) points out and explains that:

> *"Supply chain disruptions can reduce shareholder value by as much as eight to 10 percent, or even worse in "time-sensitive" environments where early market introduction is critical to success."*[6]

In this definition, the effect of disruption is considered from the shareholder's point of view. It is also emphasized that the time value is critical in supply chain disruptions and claims that companies should think and prepare themselves before the supply chain disruptions occur.

Ronald Swift (Vice president of cross-industry solutions marketing for Teradata) notes the following about supply chain disruptions:

> *"Have you considered what you would do if things went awry in your supply chain? A little preparedness could go a long way."* [7]

Disruption's effects are diversified as cost, time or emotional instability. Examples of emotional disruption results are decrease in customer trust, and workers' stress and boredom.

Many real life examples for the disruptions of the supply chain are studied in the literature. As an example, for terror event as a risk, Sheffi [13] discusses Twin Towers attack on September 11, 2001. Two trade buildings were the physical

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[6] Handfield, Rob. 2007. *Reducing the impact of disruptions in supply chain.* Sas.com Magazine. pp. 34-39.
[7] p. 1. Swift, Ron. 2006. *Managing supply chain risk.* Teradata Magazine. NCR Corporation. pp. 1-2.

location for one of the supply chain member for different companies. After this attack, unfortunately, one member of the supply chain disappeared or was destroyed. The author gives real world examples of the results of these disruptions. For instance, components of the product of Ford were delayed on Canada and Mexican borders, and the assembly lines became idle intermittently. The recovery of the manufacturing disruption brought along many different costs. Another disruption caused by September 11 attacks were experienced by the Toyota Motor Company. Toyota production was halted for many hours at its Sequoia SUV plant, in India because Toyota's supplier was waiting for its steering sensors, which were shipped from United States. However, the air traffic throughout the United States was shut down due to this terror attack. In another study, Gopalakrishnan and Oke [14] consider supply chain disruptions and risks by giving examples of the lightning strike at Phillips plant in New Mexico in March 2000, the Union carbide gas leak disaster in Bhopal, India in 1984, and more recently the contagious Avian flu in parts of Asia.

1.5 WHY SUPPLY CHAINS ARE DISRUPTED?

Supply chain disruptions may occur due to several factors. It can be caused by internal (within the firm and interaction of supply chain members) or external risk (between the supply chains of the whole business) factors. Besides, causes of disruptions can be categorized as predictable and unpredictable risks. Predictable risks are intentional expected harm from others. Unpredictable risks are all kinds of natural disasters, terror attacks, economic crisis, strikes and problems within the borders of the firms.

Another way to group risk factors causing disruptions is to divide them into natural and man-made disasters because some of them emanate from human beings and some of them emanate from nature.

Zhenling [15] classifies disasters as: tsunamis, typhoons, volcanic eruptions, earthquakes, floods and so on. In [15], author specifies that in the earthquake disruption, the area factor is very important for rescue and salvation according to supply chain members. The author also emphasizes that the integrality of supply chain before the natural disaster occurs is very important.

1.6 AIM AND CONTENT OF THE THESIS

It is important to cope with disruption before it occurs. Firms should prepare themselves for this uncertain environment. Experts develop many methods to overcome or to minimize its effects. In the studies, these methods are achieved by using mathematical programming models, fuzzy logic, simulated annealing algorithm, different kinds of probability distribution functions, statistical models or discrete event system simulation.

In this study, mathematical programming approach, specifically mixed integer programming, is selected to study supply chain disruptions, to strengthen stability of supply chain, to maximize flow and to reduce expected disruption cost. Besides, unpredictable disruptions are evaluated and the occurrences of disruptions are accepted independently of each other. There are three models in this study. One is single-product single-period, single-product multi-period and the other is multi-product single-period model.

This Thesis differs from past studies and its contribution lies in the calculation of the expected risk exposure. In addition, it is applicable to all business companies in the world trying to observe, plan, esteem, control and fortify their supply chain system. This Thesis combines flow optimization, facility location, disruption analysis, backlogging, inventory holding and trust decrease cost by using probability distribution function for assigning different probability to disruption scenarios. Besides, it has objective function of minimizing trust decrease cost, backlogging cost, fixed cost and transportation cost. It uses expected risk exposure approach to obtain expected supply chain disruption cost. Disruptions are assumed with scenarios, which are randomly occurring. Models aim to minimize the effect of each disruption scenario. Different from the related studies in the literature, this Thesis tries to provide answer to some important questions simultaneously.

1.7 ANSWERED QUESTIONS

This Thesis aims to propose solution methods for all of the following questions:

- What should be the optimal flow through the supply chain?
- How can we cope with disruption when it occurs?
- Do we new open emergency warehouses?
- How to minimize fixed cost for opening emergency warehouses?
- What should be the optimal total transportation cost between supply chain members?
- If backlogging cost occurs at any retailer, how can we minimize it?

- If retailer's trust to supply chain is reduced because of the sudden disruption in warehouse or the manufacturer location, how can we minimize the loss of trust?
- How can we minimize inventory holding cost for all members of the supply chain?
- What will be the optimal flow of the supply chain to supply its retailers and customers after the disruption?
- How can we design and coordinate the supply chain when there is more than one product type (multi-product), according to all questions that are asked above?
- What is the optimum inventory level for each warehouse?
- How can we construct a system within a recovery period of two months after disruption occurs?

CHAPTER 2

LITERATURE REVIEW ON SUPPLY CHAIN DISRUPTIONS

Disruptions in the supply chain have significant role in destroying part of whole of the chain. Supply chain disruptions are harmful for the whole of the supply chain system because the effect covers all supply chain members. Disruption of even a single member in the supply chain can affect the whole system. Especially, researchers evaluate this effect from cost perspective. However, it can also be evaluated from emotional perspective considering the time related disadvantages to the end-customers of the supply chain. Supply chain disruptions bring along themselves cost with time, excess time consumption and emotional disadvantage according to all members of supply chain. Emotional disadvantage according to customer is a decrease in trust, and emotional disadvantage for other members are stress and boredom (for instance, blue collar workers or white collar workers).

Matsypura and Nagurney [16], claim that supply chain uncertainties and disruptions occur intensively, especially at the present because of globalization. They point out the importance of the supply chain disruptions due to epidemic diseases such as SARS or other virus caused diseases.

According to Mark Hillman (AMR Research, Teradata Magazine, NCR Corporation): "Environmental disaster, any disruption of logistics, whether it be supplier shortfall or transportation — all companies need to be thinking about these things."[8] He expresses that supply chain disruptions are in wide variety and different from each other. Companies should think and try to estimate supply chain disruption occurrence, strength, duration and consequences.

2.1 CLASSIFICATION OF SUPPLY CHAIN DISRUPTIONS

NATURE-MADE DISRUPTION RISKS	MAN-MADE DISRUPTION RISKS
■ Natural disasters • Fire • Earthquake • Flood • Landslide • Avalanche • Hurricane, tornado ■ Epidemics ■ Drought etc.	■ Embargos ■ Strikes ■ Terror attacks ■ Wars ■ Crimes ■ Political conflicts ■ Inflation ■ Economic crisis etc.

Figure 3. Classification of disruption risks as nature-made and man-made

The classification of the supply chain risks is achieved in many ways as pointed out in the introduction. The most common and detailed analysis is performed by dividing

[8] p. 2. Hillman, Mark. 2006. *Managing supply chain risk.* Teradata Magazine. NCR Corporation. pp. 1-2.

risks into nature-made and man-made disruption risks as illustrated in Figure 3. In another study, Chapman [17] divides man-made disruptions into four groups. These are political, economic, social and technological man-made disruption risks. He analyzes these disruption risks in small sized or medium sized and large sized companies.

This thesis considers naturally occurring disruption risks which affects the supply chain network.

2.2 EVALUATION AND REDUCTION METHODS OF SUPPLY CHAIN DISRUPTIONS

In the literature, there exist many different methods to analyze and reduce supply chain disruption risks. For instance, Liu et al. [18] define five main methods to reduce supply chain disruption risks. These are additional capacity, having an extra supplier, safety management, increased flexibility and robust planning.

Chapman [17] points out five guidance methods to cope with disruptions for SME's (Small or Medium Sized Enterprises). These are:

- Specify potential supply chain disruptions
- Classify supply chain disruption and evaluate vulnerability
- Improve supply chain disruption risk mitigation strategies
- Improve supply chain disturbance response actions
- Conduct organizational forward planning

Teuteberg [11] mentions that risk disruptions should be evaluated with the formulation and revision of risk strategy, risk identification and monitoring, risk analysis, prioritization and assessment, risk response and action planning, scheduling, risk controlling and comparison of risk situation and risk strategy.

Wen and Xi [19] propose following disruption risk evaluation criteria in their study:

- Occurrence probability
- Damage degree
- Risk of budget allowance
- Minimal adjustment time for risk
- Involved units
- Crisis-settling mechanism.

Disruption risk values are calculated according to these criteria. The highest risk value demonstrates the most dangerous and harmful impact for supply chain.

2.3 GOALS AND CHALLENGES IN SUPPLY CHAIN DISRUPTIONS

Supply chain disruptions occur suddenly and usually independently. These two characteristics present significant disadvantages to companies. Supply chain disruption management goals are important because they prevent system operations from breaking down. Three main goals are seen while analyzing supply chain disruptions. These are coping with disruption before it occurs, perceiving all potentially identified risks and enhancing the capacity of the supply chain as much as possible by keeping the chain flexible and integrated.

Coping with a potential disruption before its occurrence is important. Required precautions and preventions should be taken for the supply chain. These aim to prepare for the possible disconnection. The second goal identifies to define all potential disruption risks. The action is taken according to existing disruption risks at each company's business area. The last goal implies the strength of flexible and integrated supply chain. These two characteristics are needed when dealing with disruptions. Enhancing capacity is required as much as possible.

2.4 SUPPLY CHAIN DISRUPTION MANAGEMENT STRATEGIES

Research studies about supply chain disruption management studies can be categorized according to:

1. supplier selection and analysis
2. internal or external risks in exporting firms
3. internal and external risks in process industries
4. fuzzy decision making
5. demand management
6. in facility location and network configuration.

Past and the present studies do not handle all of these subjects simultaneously. Again, in Gaonkar and Viswanadham's study [12], three strength levels are defined to cope with supply chain risks. These are strategic, tactical and operational. They analyze two models as strategic level deviation management and strategic level disruption management. In strategic level deviation model, they tend to minimize the expected cost of operating entire supply chain and the expected cost of risk variations. It is an adaptation of the Markowitz model. At the strategic level disruption management model, they aim to decrease the expected probability of supplier disruption in their scenarios. They use integer quadratic programming in both models and solve the problem by EXCEL. In this study, a stochastic approach and integer programming are used together. However, they do not consider transportation cost and activities. In this Thesis, we consider transportation costs based on distance between the supply chain members' locations.

Synder and Shen [20], analyze disruptions in multi-echelon supply chains. Using simulation, they analyze the recovery process by adding holding and backlogging costs. In another study, Qiang and Nagurney [21] analyze the supply chain network model with multiple-decision makers, considering all members of the supply chain when disruption occurs. They pay special attention to disruption on links and consider different transportation modes as alternatives. They minimize transaction costs for evaluating the transportation flow. They want to measure the robustness of their network design to find out the network performance.

Santoso et al. [22] study supply chain network design under uncertainty assumption. They construct stochastic programming models based on realistic perspectives. They design two real supply chain networks using a sample average approximation (SAA) and Benders decomposition algorithms. Goh et al. [23], analyze stochastic model for multi-stage global supply chain network problem with supply, demand and exchange risks and disruptions. They use Lagrangian algorithm as part of their solution.

In the study of Teuteberg [11], supply chain risk planning and optimization is studied with neural network approach. He defines the members of supply chain management and states that it is a cyclic process. He constitutes supply chain network with critical paths and forms a risk assessment matrix. This matrix denotes the probability of disruptions at a specific link between the supply chain nodes.

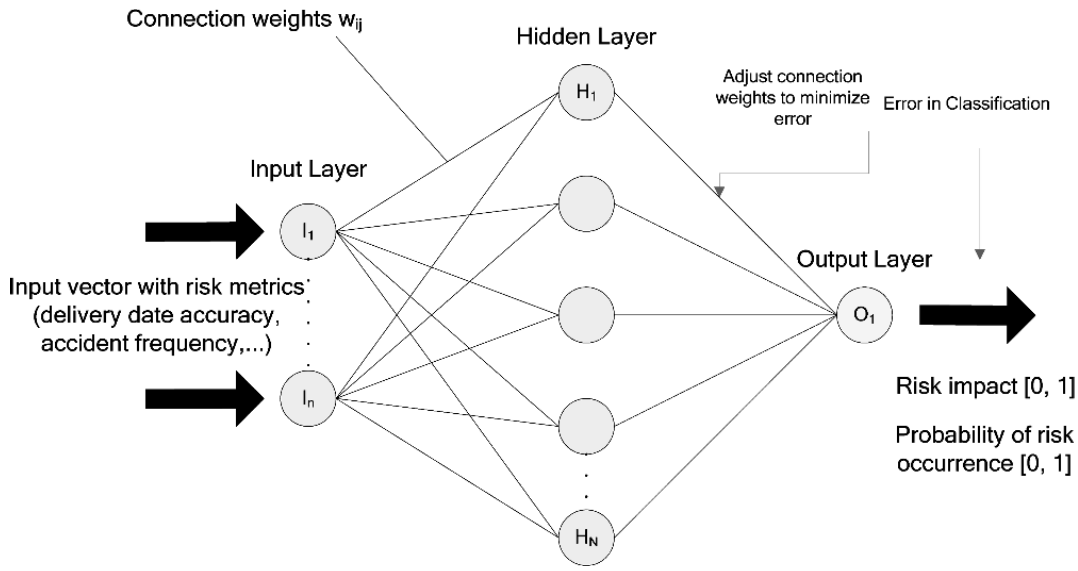


Figure 4. Neural network map with N hidden layer (Source: [11])

Then, the author specifies input layer, hidden layer and output layer as shown in Figure 4. During the calculations with “Flexsim” program, supply network demo data is generated and exported to “Excel”. Afterwards, “Neurosolutions” software is used as neural network simulator. Four hidden layers and 75 neurons are used in the applied model. This is defined as multi layer perception (MLP). The forth hidden layer is selected according to minimum disruption occurrence. Obviously, author analyzes different subject of supply chain network disruption comparing with our study.

Another study of Dong et al. [24], deals with supply chain network disruptions by using inoperability input-output modeling (IIM). IIM is used in macro economics originally. IIM’s key component is ordered weighted averaging operator for evaluating interdependency matrix. IIM evaluates the effects of supply chain network disruptions in case of “inoperability” and “economic losses” risks. They use risk mitigation strategy and they use Monte Carlo Simulation method. Inoperability input-output modeling is based on an algorithm with five steps. These steps are:

1. Setting ordered weighted averaging (OWA) weights

2. Determining evaluation matrix

3. Normalizing evaluation matrix

4. Aggregating the evaluations

5. Repeating steps 2-4 for each node of the supply chain. Interdependency coefficients for all nodes are obtained. Then, the interdependency matrix of all nodes is formed.

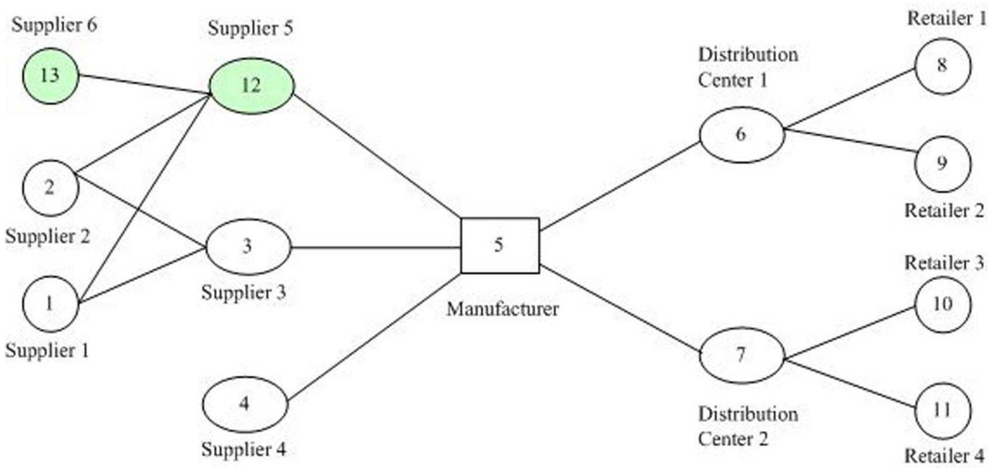


Figure 5. The risk mitigation supply chain network (Source: [24])

As a case study, they apply IIM method in one of the Chinese white alcohol production firm. They discover the risky nodes in their supply chain as node 3 and node 5 according to two criteria, as inoperability and economic losses. They then apply risk mitigation strategy to fortify the risky nodes 3 and 5. Node 3 is a supplier node and node 5 is a manufacturer node in their study. To fortify these, they add new supplier node as node 12 and 13 to decrease the risk of node 3 as a supplier for manufacturer node 5. The fortified (risk mitigated) supply chain network is shown in Figure 5.

As can be seen in Figure 5, node 12 and node 13 are the new nodes added to the system for fortification. In the last stage of the study, authors use Monte Carlo simulation by using “ExtendSim” simulation package with the same case study data to evaluate before and after taking risk mitigation strategy. Results are approximately similar with Inoperability Input-Output Modeling (IIM) method.

In another study, by Tomlin and Wang [35] deal with uncertainty in the supply chain when resource investments are unreliable and the company is “risk averse”. They combine and interpret mix-flexibility and dual sourcing approaches. They consider evaluating product portfolio of the firm’s resources. They compare single-sourcing and dual-sourcing networks. They conclude that as the supply chain reliability decreases, the need for dual-sourcing network increases.

Vito and Massimo [36] deal with the critical components of the infrastructure networks for struggling against terrorist attacks as disruptions. For national policy, they conclude that critical functioning nodes and arcs of the networks of the countries must be protected before the risk constitutes. As a result, they determine the critical links and symbolize them with a green line, and propose actions to protect and fortify these critical links.

Shen and Synder [37] analyze both supply uncertainty and demand uncertainty in the supply chains. For both supply and demand uncertainty, they propose different strategies such as centralization, inventory placement, and supply-chain structure. The authors denote that supply and demand uncertainties affect the company in completely different ways. Therefore, the company should make trade-off between them while managing supply chains under uncertainty. As a result, they guide and give advice to companies on whether to hold inventory or locate optimal area or increase the resilience of their supply chain to cope with disruptions. These advices change from one company to another.

Kleindorfer and Saad [38], consider risks arising from natural disasters, strikes, economic disruptions and terrorist actions. They propose conceptual framework and analysis of risk mitigation, evaluation and management. As a result, they explain that continuous coordination, cooperation and collaboration with in supply chain members reduce risk occurrence and maximize profit as benefits. They point out strategic actions for companies to assess their assets and also to categorize them for managing risk.

2.5 SUPPLY CHAIN DISRUPTION STUDIES ACCORDING TO SUPPLIER SELECTION AND ANALYSIS

In the research studies, there exist many ways to imply risks or disruptions within the supply chain processes. Some experts investigate this analysis on the side of suppliers. Research studies focus on supplier selection or assessment. For instance, Chopra, Reinhardt and Mohan [25] examine this subject according to supplier side by categorizing into two sides: disruptions and delays. Their aim is to compare two suppliers, one cheap and unreliable (U) and the other one is more expensive but reliable (R). The authors then make suggestions for the managers on selecting the appropriate supplier. For this study, they tend to use and adopt cumulative disruption function with mean and standard deviation. According to this study, they consider six different cases. These cases are:

Case 1: In the absence of disruption, there exists only supply uncertainty. They obtain the order quantities from the first (cheap) and second (expensive and reliable) supplier. Then, the expected total cost covering overstocking, under stocking and the expected cost on decoupling two uncertainties on suppliers are calculated. Here, there is no supplier selection.

Case 2: The absence of disruption continues, in this case, bundling and decoupling of supply chain uncertainties are analyzed. Bundling the two uncertainties, it is found that reliable supplier is not proper choice to use; instead, (first) cheap supplier should be used. On the other hand, decoupling the two uncertainties result in selection of reliable (second) supplier to use.

Case 3: In this case, disruption probability occurs for the (first) cheap supplier. The analyzers bundle the two uncertainties. The result shows that first supplier (cheap) should be selected comparing to the second (reliable, expensive) supplier. On the other side, if they decouple these uncertainties and disruption, they notice that reliable supplier should be selected.

Case 4: In the bundling phase, quantity ordered from the first supplier increase the disruption probability.

Case 5: This case is the decoupling phase. If the probability of disruption increases the quantity ordered from the first (cheap) supplier decreases.

Case 6: This case is also the decoupling phase. Here, the probability of disruption now decreases, while the quantity ordered from the first supplier increases.

After the analysis of these six cases, the authors assign random numbers to the input parameters (overage cost, shortage cost, demand, exercise price per unit and unit cost) and produce graphical results. Some graphics illustrate the probability of disruption for each of the two suppliers and some graphics illustrate standard deviation of the recurrent supply for each of the two suppliers. Besides, they also perform simulation. According to their findings, the resulting strategy is specified as follows: When the enhancement in the disruption risk occurs, it is appropriate to select the second supplier (reliable). On the other hand, when the enhancement in the supply uncertainty occurs (bundling phase), it is appropriate to select the first (cheap) supplier.

Another study of Tomlin [26] depends on supply chain disruptions according to supplier selection. The author analyzes supply chain disruption between two suppliers. These are unreliable and reliable. Unreliable supplier is cheap (U) and reliable supplier is expensive (R). There are many conditions and situations for the suppliers and the purchaser firm. All of these conditions and situations are evaluated in the study. The aim is to make the optimal purchasing decision between the suppliers and to select whether to carry inventory or not. This is implied as disruption management strategy.

Four policies are determined and the optimal decisions according to the given polices are revealed according to their theorems. These four policies are

- optimal ordering policy
- optimal base stock level when u is up
- optimal sourcing strategy
- optimal disruption management strategy.

Table 1. Optimal disruption management strategies for three flexibility cases (Source: [26])

Disruption Management Strategy	**Zero Flexibility**	**II-Flexibility**	**Partial Flexibility**
Acceptance	Yes	Yes	Yes
Mitigation only inventory	Yes	Yes	Yes
Mitigation only by sourcing exclusively from R	Yes	Yes	Yes
Contingency only rerouting	No	Yes	Yes
Inventory mitigation and contingency rerouting	No	Yes	Yes
Inventory mitigation and partially sourcing from R	No	No	Yes
Contingency rerouting and partially sourcing from R	No	No	Yes
Inventory mitigation, contingency rerouting and partially sourcing from R	No	No	Yes

Before explaining these policies, the author states three key assumptions for all of these optimal theorems, which are

1) firm is risk-neutral

2) demand is deterministic

3) supplier U has infinite capacity.

Under these assumptions, optimal disruption management strategy is evaluated according to three flexibility levels. For zero-flexibility single sourcing is optimal. Optimal disruption management strategies for three flexibility cases characteristics' are compared in Table 1.

As can be seen from Table 1, partial sourcing from supplier R is not optimal solution for zero flexibility and II-flexibility. There are also strategy terms proposed by the author. These are:

A, Acceptance: The firm passively admits the disruption risk. Firm sources exclusively from U, unreliable supplier. and carries no inventory. This way contains high risk coping with supply chain disruptions.

IM, Inventory Mitigation: The firm sources only from U, however, it also carry inventory to avoid and handle disruptions.

SM, Sourcing Mitigation: The firm sources exclusively from the R, reliable supplier.

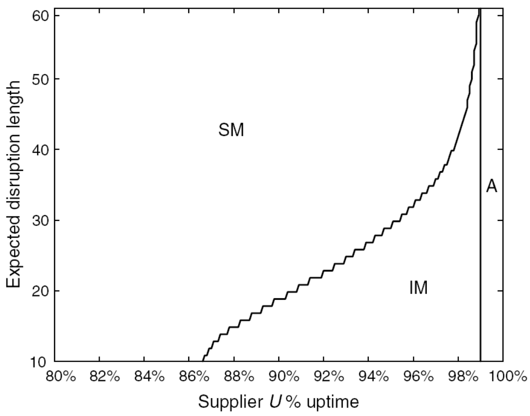
CR, Contingent Rerouting: The firm sources exclusively from U when it is up. The firm carries no inventory, but it reroutes to R during a disruption.

IMCR, Inventory Mitigation and Contingent Rerouting: The firm sources only from U when it is up. The firm also carries some inventory to avoid and handle disruptions. Besides, there is a choice for the firm, during a disruption it may also reroute production to R.

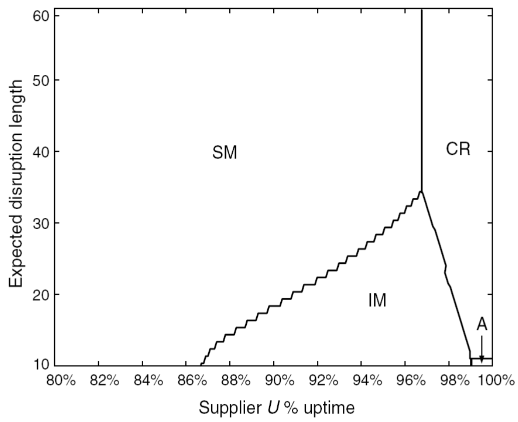
MPSI, Mitigation through Partial Sourcing: In this strategy, firm sources from both R and U, although there is no disruption. The firm also carries inventory to avoid and handle disruptions. This strategy is preferable in mean-variance approach and when supplier U has finite capacity. Partial sourcing is definitely preferable in MPSI.

MPS: In this strategy, the firm sources from both suppliers, even if there is no disruption. However, in this strategy, the firm carries no inventory to cope with the degradation in the supply chain. MPS is seen when supplier U has finite capacity.

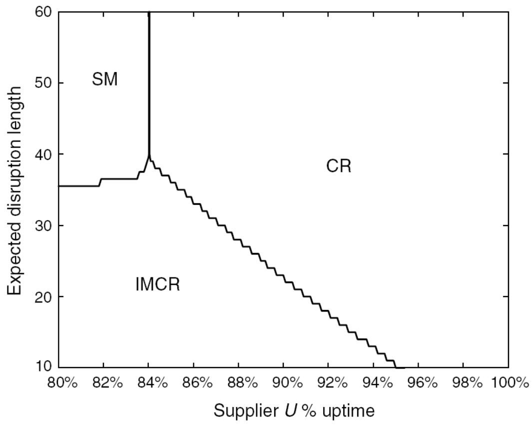
For zero flexibility, three strategy terms, sourcing mitigation (SM), inventory mitigation (IM) and acceptance (A), are included. As can be perceived by its name, zero flexibility does not include contingent rerouting (CR) or partially sourcing (IMCR) strategies. In the study, two dimensional x-y graphics are drawn to show SM, IM and A between supplier U's percentage uptime and expected disruption length. According to the Figure 6, an enhancement in the expected disruption length decreases the probability (frequency) of a disruption. Disruption distributions are different. They are frequent but short at the bottom left of the graphic, whereas they are rare but long at the top right.



(a) Zero flexibility case



(b) II-flexibility case with high rerouting cost



(c) II-flexibility case with low rerouting cost

Figure 6. Optimal disruption management strategies for unreliable supplier according to flexibility cases (Source: [26])

This means disruptions occur frequently with short disruptions lengths; but if the length of the disruption increases, then their occurrence becomes rare to the firm when selecting U. For IM and SM locations in the graphic, it can be said that IM area occurs when disruptions are short and frequent. SM area occurs when disruptions are long and rare. As can be analyzed, when disruptions are long and rare, holding inventory is not an optimal solution because it requires very high amount of inventory and this means excess cost to firm.

As analyzing all three Figures, CR, contingent rerouting strategy is not valid for zero flexibility case. Supplier R provides no volume flexibility in this case. Another comment can be made on the length of expected disruption. When the length of the expected disruption decreases, CR area also decreases. CR, contingent rerouting strategy is optimal when the expected disruption length is long. CR is optimal solution when supplier U's uptime is high. On the other hand, inventory mitigation (IM) and contingent rerouting (CR), IMCR strategy is not optimal in Figure 6 (c). Figure 6 (c) has less volume flexibility cost, therefore IMCR strategy (both carrying inventory to mitigate disruptions and/or reroute to supplier R; two cases can be applied during disruption) is optimal. When supplier U's uptime is less as percentage from Figure 6 (b) and Figure 6 (c), it can be perceived that sourcing mitigation strategy (sourcing exclusively from R) is optimal.

Another study of Tomlin [34] concentrates on "supply learning" when suppliers are unreliable. The author guides companies to forecast their demands and supplier's yield distributions based on the past experiences with the suppliers. This is a different kind of approach called "Bayesian approach", which is used to define optimal finite horizon and optimal strategies for companies to struggle with unreliable suppliers. Optimal strategies are denoted as demand control or inventory control. As a result, by the period of time, if the supplier's reliability increases, companies tend to hold fewer inventories. Here, inventory is a protector for the risks of unreliable supplier.

2.6 SUPPLY CHAIN DISRUPTION STUDIES ACCORDING TO INTERNAL OR EXTERNAL RISKS IN EXPORTING FIRMS

In the literature, numerous studies consider supply chain risks as internal and external risks and perform different analysis.

Dan and Zan [30] aim to analyze the risks in global supply chains to help the business world to mitigate supply chain risks and make risk reduction decisions. In the study, they imply the risk difference between internal logistics and international logistics. The authors carry out a survey on 497 firms dealing with export. According to the survey results, international supply chain risks, distortions and problems reported as: export documentation, 23%; transportation costs, 20%; high import duties, 17%; unable to find foreign representative with appropriate know-how to market products, 16%; delay in transfer of funds, 13%; currency fluctuations, 12%; language barriers, 10%; and difficult to service product, 10%. In addition, they determine risk types for internal and external according to the survey results. Obviously, external risks are more complex and more numerous compared to internal risks. According to their perspective, internal risks are listed as logistics, capital and information, whereas the external risks are political, economic, culture, technical, natural and demand risks. After the determination of risks, formulate the risk probability and reliability. A case study is formed with 3 suppliers, 1 manufacturer, 2 distributors, and 4 customers. The reliability values of each supply chain member are given and denoted as R_i. The reliability values for each single member of the supply chain are obtained from the survey analysis.

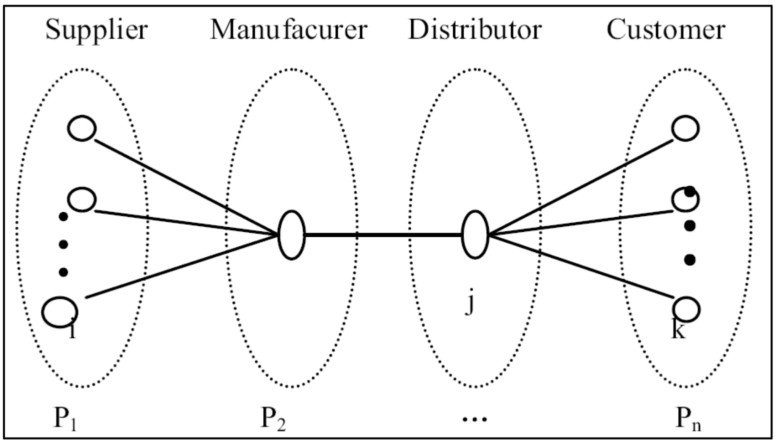


Figure 7. Supply chain network diagram (Source: [30])

Dan and Zan [30] consider the supply chain network illustrated in Figure 7. Their supply chain consists of 5 parts, which are:

- supplier part with 3 suppliers
- manufacturer part with 1 manufacturer
- distributor part with 2 distributors
- first customer part with 2 customers
- second customer part with 2 customers.

The total reliability of the whole supply chain is obtained by using the formula developed to calculate the risk. Individual network reliabilities are multiplied and then used to calculate the risk level $L = 1 - R$, where

$R = R_{P1}\, R_{P2}\, R_{P3}\, R_{P4}\, R_{P5}$.

For the case study, they find the whole supply chain risk level as 0.276, which is reported to be low. The reason for this result is the existence of alternative suppliers, distributors and customers. The concentrated point in this study especially is that alternative suppliers and information sharing lower the disruption and delay risk.

As a result, for risk mitigation, companies should think of alternatives for the components of supply chain.

2.7 SUPPLY CHAIN DISRUPTION STUDIES ACCORDING TO INTERNAL OR EXTERNAL RISKS IN PROCESS INDUSTRIES

Some studies concentrate on internal or external supply chain risks especially in process industries. For instance, Liu et al. [18], analyze Chinese Chemical process industries. They define supply chain risks in process industries as:

- Supply risk: improper selection of supplier or deficiency of supplier capability (external risk)
- Capacity risk: lack of flexibility (internal risk)
- Environmental risk: accident and pollution (external risk)
- Disruption risk: natural disaster, war and terrorism (external risk)
- Equipment failure: improper of equipment maintenance, improper operation (internal risk)
- Delay risk: Inflexibility of supply source, failure of production control, etc. (both external and internal risk).

Moreover, they propose five risk reduction methods, which are: adding capacity, having redundant supplier, safe management, increased flexibility and robust planning.

They also develop integer linear programming (ILP) model for a chemical company in Shanghai. The integer value as 0 or 1 denotes the risk reduction strategy, whether it is adopted or not. They conduct a survey study to obtain critical parameters which are then used. In the integer linear programming model, they solve the problem by using LINDO 6.1. According to the optimization program results, only three of the risk reduction methods are reported to be optimum. These are: add capacity, increase flexibility and robust planning. As a conclusion, they claim that the risk reduction strategy depends on the industry type. For risk reduction methodologies for the chemical industry, they report the executives' concern about the cost of mitigation strategy. Their aim is to guide the companies in risk mitigation strategies to minimize cost. They have consideration and desire for future work, achieving the same study implying the difference between process and discrete industries applying the same techniques.

In another study, Donk and Vaart [31] analyze supply chain uncertainty in the pigment process industry. However, they assess shared resources, uncertainty and integration. They constitute a framework to investigate what level and scope of integration can be accomplished in a supply chain dominated by shared resources, if the type and amount of uncertainty vary for different buyers. Here, the analyzed risks are both external. Before the uncertainty analysis, level of integration is divided into four logistics areas. These are:

1. Flow of goods (e.g.; packaging customization, common containers, vendor managed inventories: VMI)
2. Planning and control (e.g.; joint forecasting and/or planning, multi level supply control)
3. Organization (e.g.; partnership, quasi-firm, virtual firm, JIT II)
4. Flow of information (e.g.; sharing production plans, EDI, internet, bar-coding).

Donk and Vaart [31] divide uncertainty into four parts according to the goods flow. These are:

- Low volume / Low mix, specification
- High volume / Low mix, specification
- Low volume / High mix, specification
- High volume / High mix, specification.

For the low volume/low mix specifications, they propose simple ordering procedures such as continuous replenishment or quick response. For optimal inventory control, they propose Kanban and vendor managed inventories with shared resources. First case has a low uncertainty; therefore integration efforts are not needed.

For the second case, because of low mix specification, the critical point is the capacity. They imply that the arrangement of capacity is difficult. They also propose make-to-stock as feasible option. The risks of keeping stocks are limited in this case. They point out that integrative practices may be restricted to the physical flow of goods, such as covering delivery sizes or packaging customization because of large flow of goods.

For the third case, they note that there is a risk for make-to-stock since goods can become obsolete.

For the forth case, they denote that there exist a high uncertainty with high volume and high mix. Therefore, they emphasize a high integration need in this case. Here, the suggested methods include capacity reservation, keeping stocks (make-to-stock), vendor managed inventories, or Kanban which are seemingly not viable and sufficient anymore. Donk and Vaart [31] base their study on these four uncertainty types. They consider the chemical industry with five main buyers. The level of uncertainty and integration are analyzed with these five buyers, which are named as domestic appliances, compounding, packaging I, packaging II and garment. For all situations they draw supply chain network.

The authors conclude that buyers and manufacturers must share as much information as possible. Buyer and supplier relationship for all cases is significant to reduce any costs including manufacturing and inventory holding cost. For future research, authors suggest to study the relationship between the business conditions, level and scope of integration, and financial and supply chain performance measures between buyers and suppliers. Hence, the search criteria will include business conditions, financial and supply chain performance measures.

2.8 SUPPLY CHAIN DISRUPTION STUDIES AND FUZZY DECISION-MAKING

There exist studies assessing supply chain disruption by ranking internal and external risks using fuzzy decision making. The aim is to guide experts about the risk rank between positive ideal risk (PIR) and negative ideal risk (NIR) with normalized fuzzy risk evaluation matrix through triangular fuzzy membership function.

Wen and Xi [19] study uses these methods while appraising supply chain risks. Authors determine risk set, then risks' criteria set and weight set. Through these values they form the evaluation matrix as:

$$F = \begin{bmatrix} x_{11} \ldots\ldots\ldots\ldots x_{1n} \\ \ldots\ldots\ldots\ldots\ldots\ldots \\ x_{m1} \ldots\ldots\ldots\ldots x_{mn} \end{bmatrix}$$

where, x_{ij}, triangular fuzzy number of j^{th} risk under j^{th} criteria.

Normalizing the fuzzy risk evaluation matrix they compare each risk with the positive ideal risk and negative ideal risk making supply chain enterprise main risks rank more reasonable, thus enterprise can take corresponding measure to the high rank risks. They weight the fuzzy evaluation matrix. They find out fuzzy ideal risk M^+ (maximum of fuzzy set according to j^{th} criteria) and M^- (minimum of fuzzy set according to j^{th} criteria). Their aim is to aid experts and business in supply chain risk management with calculating and comparing the risks.

Authors apply these methods to a specific case study. They first manifest the ways of applying fuzzy model for decision making to the risks. They consider following four risks:

- financial risk (considered internal)
- time risk (considered both internal and external)
- logistics risk (considered both internal and external)
- information risk (considered both internal and external).

Then, they constitute risk evaluation matrix with the following criteria:

- occurrence probability; this should be less for better result
- damage degree; this should be lighter for better result
- risk of budget allowance; this should be higher for better result
- minimal adjustment time for risk; this should be longer for better result
- involved units; this should be less for better result
- crisis-settling mechanism; the more integrity the enterprise has, the stronger the capability of dealing with all risks.

They explain risk set, corresponding risks criteria set and weight set. They then form normalizing matrix. They determine the limits of the risks as positive ideal risk and negative ideal risk and compare the risks with these values. Then, they find out the fuzzy ideal risk. According to the fuzzy multi-criteria lattice-order decision-making, they report that the highest risk is the time risk; the second is the information risk; the third is logistics risk and the last one is financial risk. Finally, they assert, that the proposed methodology can help business managers in decision making phases when there is supply chain risks occurrence.

2.9 SUPPLY CHAIN DISRUPTION STUDIES AND DEMAND MANAGEMENT

Supply chain disruptions occur on the demand side and the inventory level in the supply chain. The risk is evaluated according to inherent and exogenous risks. Simple one-echelon supply chain is evaluated according to long term average cost.
With this point of view, Chen and Zhang [32], exemplify and deal with supply chain risk on demand side. They use four main methods to obtain the optimal results. The first method is Wiener process and its generalized form. Secondly, the zero-one jump law is used to generate jumps in the simulation application. Thirdly, the Laplace distribution, which is used to depict the Jump distribution, is applied. Lastly, problem formulation and simulated annealing are implemented. They develop the model as two parts, the first part is the diffusion process and the second part is the jump process. The occurrences of jumps are governed by a Poisson process, and the jump size can be constant and follows a certain distribution, i.e. Laplace distribution. They formulate a typical optimization problem with the objective function as minimization of costs and required constraints.

They categorize costs into five groups. These are backlog penalty cost (when inventory level is below zero), holding cost, production cost, switching cost per time (when machine on and off) and the long term average cost. Hence, for analyzing the value of long term average cost they realize that a jump with right time, right direction, and right magnitude might reduce the total cost. They also detect that negative jumps will deteriorate the production process more than the positive jumps. When they run simulated annealing algorithm, the cost of backlog is observed to be higher than the inventory holding cost. In their study, a specific parameter setting has been used to illustrate the effects of jumps on the performance of supply chain. Thus, with both algorithms, it is noted that the positive jump has more disadvantages compared to the negative jumps. Extension to multi-echelon supply chain with feasible production rate is proposed as a future research study.

2.10 SUPPLY CHAIN DISRUPTIONS IN FACILITY LOCATION AND NETWORK CONFIGURATION

Supply chain disruptions can also be analyzed from the network configuration and facility location perspective. After any disruption in network and facility location, performance of the supply chain should be measured. This performance will mostly be based on reducing costs and maximizing total flow under the disruption case. Here one network configuration study is assessed without disruption to reveal supply chains configuration rules and requirements.

Snyder et al. [27] investigate this subject according to risk criteria as expected cost or worst-case cost in their study. Their aim is to find out optimal network and facility location, planning and control.

In Snyder et al. [27], the authors divide their study into two main parts. These are design models and fortification models. Within these two main parts they constitute two subparts as expected cost models and worst-case cost models. Before explaining these parts, it is required to define notations used in the study. These are:

I: Set of customer locations (these model types are explained below)

J: Potential facility locations (in fortified models in means existing facility locations)

i: Each customer

j: Each facility

d_{ij}: Distance between facility j and customer i

d_i^k: Expected transportation cost between customer i and the closest operational facility given that k-1 closest facilities to i are not protected and the k^{th} closest facility to i is protected

f_j: Annual fixed cost of each facility j

q: A fixed disruption probability of each open facility

q_s: The probability that scenario s occurs

θ_i: Penalty cost per unit demand if customer i is not served

u: Dummy source node (dummy has no fixed cost f_u=0)

v: Dummy sink node (to meet supply, for absorbing excess supply) r: Level of facilities that are closer to customer

r_{ij}: Penalty denoting the percentage capacity decrease of the arc deriving from interdiction

X_j: 1, if facility j is opened; 0, otherwise (for network design model it means 1, if node is opened; 0, otherwise)

Y_{ijr}: 1, if customer i is assigned to facility j at level r; 0, otherwise

Y_{ij}: 1, if customer i is assigned to facility j; 0, otherwise

Y_{ijs}: 1, if customer i is assigned to facility j at scenario s; 0, otherwise

b_j: Units of demand supplied by facility j

h_i: Annual unit of demand of customer i

S: Set of failure scenarios

a_{js}: 1, if facility j fails in scenario s; 0, if facility not fails in scenario s.

$G = (V, A)$ general network. V serves as source, sink or transshipment node set. A represents the arc set.

k_j: Each nonsink node j capacity

Z_j: 1, if facility j is fortified; 0, otherwise

W_{ik}: 1, if the k-1 closest facilities to customer i are not protected but the kth closest facility is; 0, otherwise.

W: Total flow through network

Q: Number of fortified facilities

P: Number of facilities in the system which have unlimited capacity

R: Unprotected facilities

H: Worst case losses after the interdiction of R facilities obligated

T_j: The level of capacity that is protected at node j

F: Covering all Z facilities which are fortified

D: Covering all R facilities which are unprotected according to scenario s

U: Maximum cost amount

B: Total protection budget

o: Supply node

d: Demand node

p_{ij}: Penalty cost of arc (i, j) to ship flow if the arc is interdicted

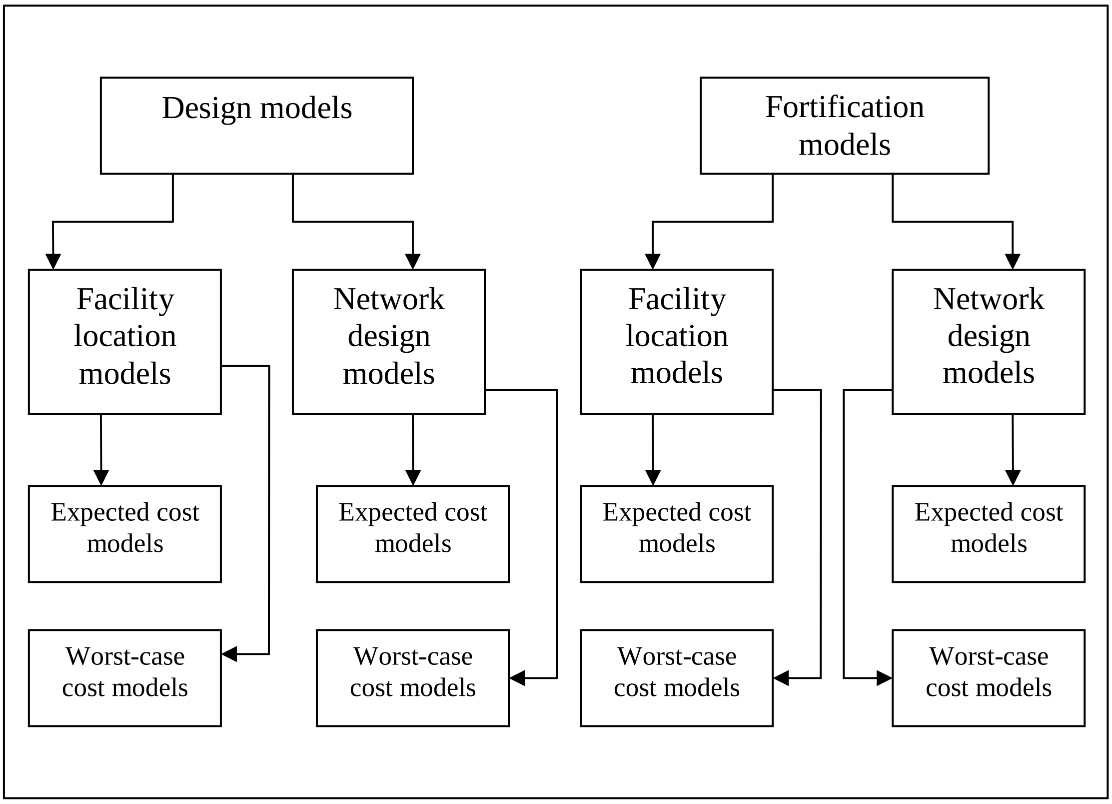


Figure 8. Model categorization

Authors categorize their model and follow an order while explaining their study. For better understanding, this categorization is mapped out and shown in Figure 8.

Design Models for Facility Location

In these models the aim is to choose a set of facility locations when no facilities currently exist. The authors evaluate facility locations after disruptions occur in supply chain. They are divided to two types as expected cost models and worst-case cost models.

Expected Cost Models for Facility Location Design

Here, authors analyze "reliability fixed-charge location problem" abbreviated as RFLP. The aim of RFLP is to choose facility locations and customer assignment to decrease the costs as fixed cost, expected transportation cost and lost-sales penalty. The RFLP is as follows:

$$Minimize \sum_j f_j X_j + \sum_{i \in I} \sum_{r=0}^{|J|-1} \left[\sum_{j \in J \setminus \{u\}} h_i d_{ij} q^r (1-q) Y_{ijr} + h_i d_{iu} q^r Y_{iur} \right] \quad (1)$$

subject to

$$\sum_{j \in J} Y_{ijr} + \sum_{s=0}^{r-1} Y_{ius} = 1 \qquad \forall i \in I, r = 0, ..., |J|-1 \qquad (2)$$

$$Y_{ijr} \le X_j \qquad \forall i \in I, j \in J, r = 0, ..., |J|-1 \qquad (3)$$

$$\sum_{r=0}^{|J|-1} Y_{ijr} \le 1 \qquad \forall i \in I, j \in J, r = 0, .., |J|-1 \qquad (4)$$

$$X_j \in \{0,1\} \qquad \forall j \in J \qquad (5)$$

$$Y_{ijr} \in \{0,1\} \qquad \forall i \in I, j \in J, r = 0, ..., |J|-1 \qquad (6)$$

The objective function aims to minimize the sum of fixed cost, transportation and lost-sales costs. The second constraint means that each customer is appointed to some facility at level *r* unless *i* has been appointed to a dummy, emergency facility. Constraint 3 is established to prevent an assignment of a facility that has not been opened. Constraint 4 interdicts customer from being appointed to the same facility at more than one level. Constraints 5 and 6 are for integrality and nonnegativity, respectively. Also, the worst case cost model for facility location design is observed in this study.

Design Models for Networks

Here authors analyze network design models with general network *G* = (*V*,*A*) in which *V* exhibits set of source, sink or transshipment nodes and *A* represents the set of arcs. Source nodes can be considered as facilities and sink nodes can be considered as customers. The main difference between network design models and facility location models is the existence of transshipment nodes. The nonsink nodes can encounter to fail randomly. Decisions on nonsink nodes form the first-stage variables and the flow on each arc in each scenario forms the second-stage variables.

Expected Cost Model for Network Design

Here each node $j \in V$ has supply of b_j which is designated above in the variables list. Also each nonsink node has capacity of k_j. Besides, here q_s, symbolizes probability of scenario s occurrence. Expected cost model for network design is named as Reliable Network Design Model (RNDP). It is as follows:

$$Minimize \sum_{j \in V_0} f_j X_j + \sum_{s \in S} q_s \sum_{(i,j) \in A} d_{ij} Y_{ijs} \tag{7}$$

subject to

$$\sum_{(j,i) \in A} Y_{jis} - \sum_{(i,j) \in A} Y_{ijs} = b_j \qquad \forall j \in V / \{u,v\}, s \in S \tag{8}$$

$$\sum_{(j,i) \in A} Y_{jis} \le \left(1 - a_{js}\right) k_j X_j \qquad \forall j \in V_0, s \in S \tag{9}$$

$$X_j \in \{0,1\} \qquad \forall j \in V_0 \tag{10}$$

$$Y_{ijs} \ge 0 \qquad \forall (i,j) \in A, s \in S \tag{11}$$

In RNDP, the objective function aims to minimize total fixed cost and total expected flow cost. Constraint 8 specifies flow-balance. They need net flow node j which is found by calculating flow out minus flow in. It is equal to node deficit b_j (same as node supply) in each scenario. Constraint 9 forces node capacities and avoid flow from source nodes that have not been opened or have failed. Inequalities given in (10) and (11) denote integrality and nonnegativity constraints. For two dummy nodes, no restrictions exist. Also, the worst case cost model for network design is achieved in this study.

Fortification Models for Facility Location

Second part of the study is fortification. The main purpose is to decide which facilities to fortify against disruptions. Planning facility fortification gives firms a great power and challenge to cope with disruptions, threats and hazards.

Expected Cost Models for Facility Location Fortification

The expected cost model facility location fortification is CRFLP. That is same as PMFP in terms of its purpose. However, now, scenarios occur in the model. Here facilities have different failure (disruption) probabilities. The main purpose of fortifications is to decrease this failure probability. However, fortification unfortunately has no force to remove probability of failure. Here scenario-based CRFLP is as follows:

$$Minimize \sum_{s\in S} q_s \sum_{i\in I} \sum_{j\in J} h_i d_{ij} Y_{ijs} \tag{12}$$

subject to

$$\sum_{j\in J} Y_{ijs} = 1 \qquad \forall i \in I, s \in S \tag{13}$$

$$\sum_{i\in I} h_i Y_{ijs} \le (1-a_{js}) b_j + a_{js} b_j Z_j \qquad \forall j \in J, s \in S \tag{14}$$

$$\sum_{j\in J} Z_j = Q \tag{15}$$

$$X_j \in \{0,1\} \qquad \forall j \in J \tag{16}$$

$$Y_{ijs} \in \{0,1\} \qquad \forall i \in I, j \in J, s \in S \tag{17}$$

CPMFP uses same scenario parameters as a_{js}, b_j and set S. However, as can be perceived logically, there are differences. For example, fixed cost is charged for locating facilities. Fortification assumes that all facilities have already been located. No location difference or alteration occurs. For this reason, there is no fixed cost in objective function. Constraint (14) specifies if facility is fortified $Z_j = 1$, it is operable to supply customer i, even it is considered its failure $a_{js} = 1$. Constraint (15) designates fortified facilities must equal to Q, fixed number. Also, the worst case cost model for facility location fortification is achieved in this study.

Fortification Models for Network Design

In this part of the study, authors analyze network design models according to risk and vulnerabilities. Interdictions or disconnections are important for the network components as nodes and links. If nodes or arcs are disabled, obviously, this causes great harm through all network covering both suppliers as facilities and customers. Authors develop models to fortify network design. Both expected cost and worst-case cost model cases are indicated within this subject.

As a result, it is tended to illustrate the strategic planning by the mathematical programming models in supply chain. Authors handle both facility and network side under the threat of disruption whether it is natural disruption or intentional. For the future research and improvement of the study, other types of constraints can be added. These can be destroyed or suffered inventory cost, reconstruction cost of the disturbed facility, customer lost cost, machine break-down cost after responsibility of supplying to customer for the reason of disruption. Also competitive environment is also significant. Firms are in race not to be worse than its competitor after disruption. Here all models are discussed according to cost side of these disruptions.

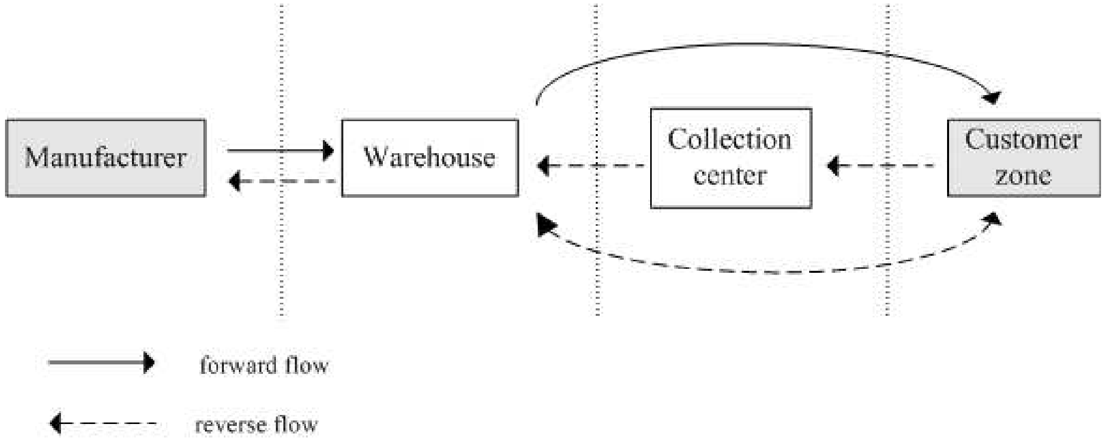


Figure 9. Product recovery network model (Source: [28])

Another study due to Beamon and Fernandes [28], discusses the supply chain configuration from a different perspective. They consider flow within the supply chain in two directions as shown in Figure 9. Here, electronic products are flowing through three-echelon supply chain network. The reverse flow occurs when customers return the used products. Then, customers send these products back to remanufacturing either through collection center or directly to warehouse. From the warehouse the products are directly send back to the manufacturer and remanufacturing process begins. There is a difference between the warehouse and the collection center. Collection centers have more capabilities and flexibility than storage warehouses. These capabilities are inspection, testing and sorting. In this study authors extend the model by;

- Opening new warehouses and collection centers by analyzing both their location and minimizing cost.
- Minimizing operational costs, which are maintenance cost in warehouse, maintenance cost in collection center, sorting cost in collection center, holding cost in all members of network (all facilities). Warehouses also have sorting capabilities.

- Considering transportation costs between all members of the network and also penalty cost from the reverse direction of the incorrect (error product) product. It is formed in the distance from customer to warehouse in reverse direction.
- Assuming holding cost in warehouses and collection centers when used products are transported from customers in reverse direction. Used products and new products both get through sorting process. If they are in good condition for remanufacture, they are accepted. Others are rejected. Accepted and new products are considered to have same holding cost.

They handle all these variables in multi-period integer programming model with both continuous and binary decision variables. This type of analysis is deterministic because all variables are known and finite. No input has probability value so this model is not stochastic problem. In the model, for investment cost and operational cost present worth method (PWH) is used.

The aim of this study is to determine which potential facilities as warehouses and collection centers to open, which warehouses to have sorting capacity, how many products are to be transported between the sites and how can the costs be minimized.

For the multi period integer programming objective function and constraints are constituted. Objective function is the minimization of summation of the opening cost, installation cost, maintenance cost, sorting cost, holding cost and transportation cost. Constraints are flow balance, opening, installation, inspection, capacity and nonnegativity. Authors define four different problems. These are:

1. Main (in this problem maintenance cost is the highest valued member of the operational cost)

2. ITS (inspection/testing/sorting cost is the highest valued member of the operational cost)
3. Trans (transportation cost is the highest valued member of the operational cost)
4. Hold (holding cost is the highest valued member of the operational cost)

In the same study, along with multi-period integer programming model, sensitivity analysis is also accomplished by attaining high, medium and low sensitivity level definition to these four types of problems.

For conclusion, according to all four types of problems different results are found out. For "main problem" the result shows that it is avoided to use warehouses. For "ITS type problem" the result illustrates that it is avoided to use warehouses again. For "trans type" the result denotes that it is converged to use warehouses. For "hold type problems" it is avoided to use collection centers. The authors aim to help and give direction to business for their supply chain configuration. Examples can be which members should allocate, which members to be open and which members have some kind of capabilities. Besides, disruption is not handled however network configuration is assessed. Therefore, it is added to under this caption of this part.

Another study of Qi, Shen and Snyder [29], defines location of retailers in the supply chain network in order to minimize the costs of location, transportation and inventory. Disruptions are assumed to occur on suppliers or retailers. Their aim is to minimize costs corresponding to these disruptions and to determine optimal facility location and optimal demand allocation.

In their model, costs are defined as:

- fixed cost for open retailers,
- working inventory cost including ordering, holding and backorder at the retailers,
- lost-sales penalty cost not to serve some customers.

Time horizon is one year in this study. In the first part, they create linear programming model. For calculating working inventory cost, they define inventory cycle length which is the duration between two consecutive shipments from supplier to retailer j. This variable is new. One of the differences of this study is using this variable and adding the time constraint. Goods flowing from retailer to supplier are considered as cycle process. These cycles are defined as ON and OFF. ON means cycle is working, flow is available. OFF means cycle is disrupted. They arrange recovery and disruption rate for supplier and retailer by using exponential distribution. All the parameters are defined on the annual basis. For the second part, authors use Lagrange multipliers w and obtain Lagrangian dual problem. As a result of this part, they report two foresights. When supplier is disrupted more often, or the recovery process for both supplier and retailer turn out to be slower; it is convenient to serve fewer customers. Other foresight is that retailers tend to be opened at locations with agile recoveries and consequently, customers tend to be served by retailers with higher recovery rates.

Like the other studies in the literature, this study is also applicable to several business areas.

CHAPTER 3

SUPPLY CHAIN NETWORK DISRUPTION MODELS AND EXPECTED RISK EXPOSURE

In this chapter, three comprehensive mathematical models are presented. In these models, goods flow is analyzed as a flow type. Besides, these network models demonstrate how to act when supply chain disruptions occur. As an easy and operable model, it can be adapted for all supply chain areas including manufacturers, warehouses and retailers in real life. Also, manufacturers, warehouses or retailers name can be changed by the user in real life; like supplier, wholesaler and customer. For these purposes, mixed integer programming is formed. Goods originate from manufacturer, then go to warehouses and then shipped to retailers. The flow direction is from left to right every time after every member of the supply chain. This type of network is hub-and-spoke network as pointed out by Lawrence V. Snyder [33]. Lawrence V. Snyder [33] proposes this type of networks in his study. Besides, all parameter values for all models are generated randomly. Companies can implement their own parameter values to these three models to obtain optimal results.

3.1 SINGLE-PRODUCT SINGLE-PERIOD NETWORK DESIGN MODEL

The transshipment nodes are warehouses and their function is to collect, hold and distribute. Every warehouse is supplied from one manufacturer only. The network configuration can be seen in Figure 10.

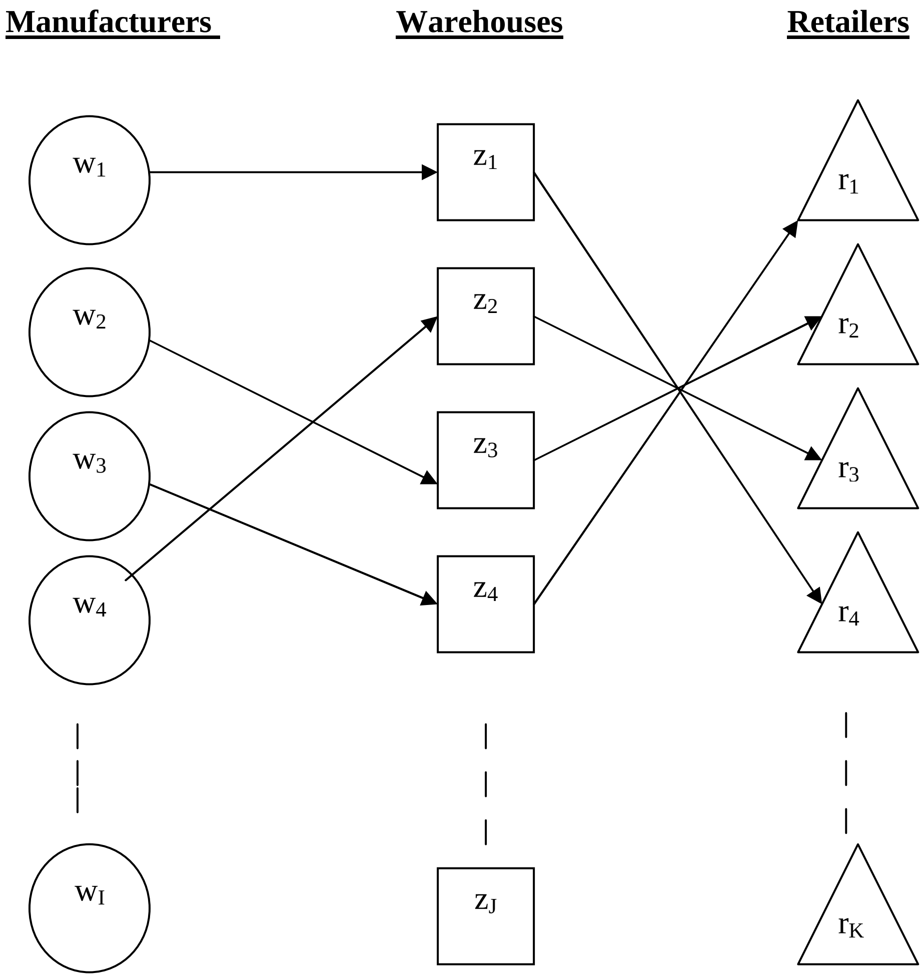


Figure 10. Single-product network model schema

Disruption occurrences are provided by the randomly generated scenarios. Every scenario is different from its preceding one. Thus, they are formed by assigning node failures to either manufacturers or warehouses. The model assumptions are stated below.

Assumptions

1. There exist three members to constitute the supply chain. These are manufacturers, warehouses and retailers.
2. Single-product is flowing through out the network.
3. It is assumed that disruption only occurs on nodes not on the arcs (links). So disruption can occur only on manufacturer nodes or warehouse nodes of the network.
4. Warehouse is served by only one manufacturer. It is not allowed to serve warehouses from more than one node.
5. Lead time is considered to be zero.
6. Backlog cost does not depend on time but it depends on unsatisfied demand quantity. Backlogging cost exist only on retailer nodes.
7. Goods can flow only in one direction that is from left to right. Reverse direction is not allowed.
8. Manufacturers and warehouses are accepted as they belong to the same company.
9. Dummy (emergency) members are considered for warehouses only. When any warehouse is disrupted, emergency warehouse is assumed to back up the operations according to optimal warehouse location. Disruptions at manufacturers cannot be backed up by dummy (emergency) plants. Note that there is no disruptions occurrence on retailer nodes.
10. There is no obligation for serving all retailers. The retailers are also connected to end customers, which are not indicated in our network model. Every three retailer

is serving to one customer. Therefore serving from one or two retailer absence forms no problem according to customer side.

3.2 ANALYSIS AND EVALUATION OF TRUST REDUCTION COST

There are many studies in the literature analyzing trust reduction cost or customer satisfaction value. Grigoroudis and Siskos [40] evaluate customer satisfaction by using “Musa method”. This method depends on the customer judgements and preferences obtained by conducting surveys. They divide customer types into three:

- Natural customers
- Demanding customers
- Non-demanding customers

They form graphs for all three kinds of customers, the ideal way is to find out natural customers because they are all satisfied with the product or service that they demand. They need no more or no less. Demanding customers are not satisfied from the products because they demand more products and provided service is below their limits. Non-demanding customers are not satisfied because the product amount or service or more than they demand. For evaluating customer satisfaction by Musa method, they first conduct surveys. Then they calculate average satisfaction, demand and improvement indices. They find out importance and effects of the criteria according to customer type. As a result, they claim, they take the same actions as benchmarking and Musa method is one of the appropriate methods for customer satisfaction.

In this Thesis, similar to customer satisfaction, costumer trust reduction cost can also be gained by surveys and evaluation methods. In this thesis trust reduction costs are assumed to be known and given.

3.3 CONTENTS AND MATHEMATICAL FORMULATION OF SINGLE-PRODUCT SINGLE-PERIOD NETWORK DESIGN MODEL

Here, this model serves two purposes. One is to ensure regulation of flow of goods properly. The other aim is to minimize the occurrence of supply chain disruption by scenarios. This model achieves this aim by substituting disrupted warehouses with emergency warehouses. Objective function is set to reduce cost including which are transportation cost, backlog cost and customer trust reduction cost.

In the model decision variables are:

$$w_{ij}: \begin{cases} 1, \text{ if warehouse } j \text{ is assigned to be served by manufacturer } i; \\ 0, \text{ otherwise} \end{cases}$$

$$z_j: \begin{cases} 1, \text{ if the emergency warehouse } j \text{ is opened to serve, } j < m; \\ 0, \text{ otherwise} \end{cases}$$

z_j: Open warehouses (instead of emergency warehouses) $j \geq m$;

The following input parameters are used in the model:

I: Total number of manufacturers

i: Each of the manufacture

J: Total number of warehouses

j: Each of the warehouse

K: Total number of retailers

k: Each of the retailer

M: Total number of emergency (dummy) warehouses

m: Index for emergency (dummy) warehouse

S: Total number of scenarios

X_{ij}: Number of products flow from manufacturer i to warehouse j

Y_{jk}: Number of products flow from warehouse j to retailer k

b_k: Backlog cost of retailer node k

Q_i: Units of supply from manufacturer at node i

P_j: Units of storage capacity of warehouse at node j

d_k: Units of demand from retailer at node k

U_{jk}: Trust reduction value of retailer at node k from not being served by warehouse j

(it is zero if the scenario s is not occurred, no disruption case)

a_{is}: Scenario s occurrence value on manufacturer node i

$a1_{js}$: Scenario s occurrence value on warehouse node j

$g1_{ij}$: Distance from manufacturer node i to warehouse node j

$g2_{jk}$: Distance from warehouse node j to retailer node k

f_m: Fixed cost of new (emergency) dummy facility to be opened

V: Very big number to ensure solution balance

Model 1:

$$Minimize \sum_{i,j} g1_{ij} X_{ij} + \sum_{j,k} g2_{jk} Y_{jk} + \sum_{j=m}^{M} f_j z_j + \sum_{k,j} b_k \left(d_k - Y_{jk}\right) + \sum_{j,k,s,i} U_{jk} \left(a1_{js} + a_{is}\right)$$

subject to

$$\sum_{j}^{J} X_{ij} \leq Q_i \ (1 - a_{is}) \quad \forall\ i \in I \quad \forall s \in S \qquad (1)$$

$$\sum_{k}^{K} Y_{jk} \leq P_j\left(1 - a1_{js}\right) \quad \forall j < m \quad \forall s \in S \tag{2}$$

$$\sum_{k}^{K} Y_{jk} \leq P_j z_j \quad \forall k \in K \quad \forall j \geq m \tag{3}$$

$$\sum_{j}^{J} Y_{jk} \leq d_k \quad \forall k \in K \tag{4}$$

$$\sum_{i}^{I} X_{ij} \leq P_j z_j \quad \forall j \in J \tag{5}$$

$$\sum_{i}^{I} X_{ij} = \sum_{k}^{K} Y_{jk} \quad \forall j \in J \tag{6}$$

$$\sum_{i}^{I} w_{ij} = 1 \quad \forall j \in J \tag{7}$$

$$z_j \geq w_{ij} \quad \forall j \in J \quad \forall i \in I \tag{8}$$

$$V w_{ij} \geq X_{ij} \quad \forall j \in J \quad \forall i \in I \tag{9}$$

$$V z_j \geq Y_{jk} \quad \forall j \in J \quad \forall i \in I \tag{10}$$

$$X_{ij} \leq V(w_{ij}(1 - a_{is})) \quad \forall i \in I \quad \forall j \in J \quad \forall s \in S \tag{11}$$

$$Y_{jk} \leq V(z_j(1 - a1_{js})) \quad \forall j \in J \quad \forall s \in S \quad \forall k \in K \tag{12}$$

$$X_{ij} \geq 0 \quad \forall i \in I \quad \forall j \in J \tag{13}$$

$$Y_{jk} \geq 0 \quad \forall j \in J \quad \forall k \in K \tag{14}$$

$$w_{ij} \in \{0,1\} \quad \forall i \in I \quad \forall j \in J \tag{15}$$

$$z_j \in \{0,1\} \quad \forall j \in J \tag{16}$$

- Constraint (1) implies that flow amount from each manufacturer *i* depends on the manufacturer capacity. That is, flow amount must be less than or equal to manufacturer capacity considering disruption according scenario s.

- Constraint (2) denotes that flow amount from each warehouse *j* depends on the warehouse capacity. It must be less than or equal to warehouse capacity. Moreover, it must conform to disruption scenario *s*.
- Constraint (3) designates the dummy (emergency) warehouse. It is explained that dummy warehouses are not affected from disruption. They are constructed after the disruption hits therefore they are protected. Each dummy warehouse has a capacity and the flow amount cannot exceed its capacity.
- Constraint (4) is established for the satisfaction of the retailer demand. Note that we allow retailer's demand may not be satisfied 100%. In other words, total flow amount sent from each warehouse *j* to each retailer cannot exceed retailer's demand.
- Constraint (5) explains that flow amount from each manufacturer *i* to each warehouse *j* cannot exceed warehouse capacity.
- Constraint (6) is formed to ensure the flow balance at each warehouse node. It also prevents backlogging at each node of warehouse *j*.
- Constraint (7) means that each warehouse *j* can only be served by one manufacturer *i*.
- Constraint (8) ensures that manufacturer *i* cannot be allocated to warehouse *j* if the related warehouse is not in service or not opened.
- Constraint (9) denotes that there will be product flow from manufacturer *i* to warehouse *j* if and only if manufacturer *i* is not disrupted and it is allocated to serve warehouse *j*.
- Constraint (10) indicates that each warehouse should be open or not disrupted first to send products to retailers.

- Constraint (11) and (12) ensures not to send products for both manufacturers and warehouses if they are disrupted.
- Constraints (13) and (14) imply nonnegativity for decision variables X_{ij} and Y_{jk}.
- Constraints (15) and (16) represent that decision variables w_{ij} and z_{jk} are binary variables.

Model 1 GAMS codes are denoted in Appendix A.

3.4 SINGLE-PRODUCT MULTI-PERIOD NETWORK DESIGN MODEL

This model serves for two purposes. One is to ensure regulation of flow of goods properly. The other aim is to minimize the occurrence of supply chain disruption by scenarios depending on time periods (per month). This model achieves this aim by immediately substituting disrupted warehouses with emergency warehouses. Besides, inventory holding cost and the controlling the level of inventory appear in warehouse nodes. Objective function is set to reduce total cost including manufacturing cost, transportation cost, inventory holding cost, backlog cost and customer trust reduction cost for all time periods. The assumptions for Model 2 are given below:

Assumptions

1. It is assumed that disruption only occurs on nodes not on the arcs (links). Therefore, disruptions can occur on manufacturer nodes and warehouse nodes. It is assumed that no disruption occur on retailer nodes.
2. Warehouse is served by one manufacturer only.
3. Lead time is considered to be zero.

4. Single-product is flowing through out the network.

5. Backlogging cost exists only on retailer nodes.

6. Inventory holding cost only exists on warehouse nodes. Other two nodes as manufacturers and retailers have no inventory holding cost.

7. There exist three members to constitute the supply chain. These are manufacturers, warehouses and retailers.

8. Goods can flow only in one direction that is from left to right. Reverse direction is not allowed.

9. Two members of the network as manufacturers and warehouses are accepted as they are different plants of the same company.

10. Dummy (emergency) network member can only be from warehouses and they are certain and determined (as which ones and their quantity). Other two members (as manufacturers or retailers) cannot be dummy member. Dummy warehouses are protected; they cannot be affected from disruptions.

11. There is no obligation for serving all retailers. Since the retailers are also connected to end customers which is not indicated in our network model. Every three retailer is serving to one customer. Therefore, serving from one or two retailer absence forms no problem according to customer side.

12. Time period is considered as a month and total time horizon is one year throughout the supply chain network.

13. After disruption occurrence, it is assumed one month for every manufacturer as recover period and two months for every warehouse as recover period.

14. For this single product, there is a production cost differs on each manufacturer and each period of time.

3.5 MATHEMATICAL FORMULATION OF SINGLE-PRODUCT MULTI-PERIOD NETWORK DESIGN MODEL

In the model decision variables are:

$$w_{ijt} = \begin{cases} 1, & \text{if warehouse } j \text{ is assigned to be served by manufacturer } i \text{ at time period } t \\ 0, & \text{otherwise} \end{cases}$$

$$z_{jt}: \begin{cases} 1, & \text{if the warehouse j is opened to serve at time period t (including emergency (dummy) warehouse, } m \text{ ; } j \leq m \\ 0, & \text{otherwise} \end{cases}$$

X_{ijt}: Number of products flow from manufacturer i to warehouse j at time period t

Y_{jkt}: Number of products flow from warehouse j to retailer k at time period t

Inv_{jt}: Inventory level at warehouse node j at time period t

Model parameters are:

I: Total number of manufacturers

i: Each of the manufacture

J: Total number of warehouses

j: Each of the warehouse

K: Total number of retailers

k: Each of the retailer

M: Total number of emergency (dummy) warehouses

m: Each of the emergency (dummy) warehouse

S: Total number of scenarios

s: Each of the scenario

T: Total time period as 12 all months in a year

t: Each time period as a month of a year

h_{jt}: Inventory holding cost of warehouse node *j* at time period t

b_{kt}: Backlog cost of retailer node *k* at time period *t*

Q_{it}: Units of supply from manufacturer at node at time period *t*

P_{jt}: Units of storage capacity of warehouse at node *j* at time period t

d_{kt}: Units of demand from retailer at node *k* at time period *t*

U_{jk}: Trust reduction cost of retailer at node *k* from not being served by warehouse *j* (it is zero if the scenario s is not occurred, no disruption case)

a_{ist}: Scenario s occurrence value on manufacturer node *i* at time period *t*

$a1_{jst}$: Scenario s occurrence value on warehouse node *j* at time period *t*

$g1_{ij}$: Distance from manufacturer node *i* to warehouse node *j*

$g2_{jk}$: Distance from warehouse node *j* to retailer node *k*

f_m: Fixed cost of new (emergency) dummy facility to be opened

E_i: Unit manufacturing cost of the product at manufacturer node *i*

V: Very big number to ensure solution balance

Model 2:

$$Minimize \sum_{i,j,t} E_i X_{ijt} + \sum_{i,j,t} g1_{ij} X_{ijt} + \sum_{j,k,t} g2_{jk} Y_{jkt} + \sum_{j=m,t} f_j z_{jt} +$$

$$\sum_{i,j,t} h_{jt} Inv_{jt} + \sum_{k,j,t} b_{kt} \left(d_{kt} - Y_{jkt} \right) + \sum_{j,k,s,i,t} U_{jk} \left(a1_{jst} + a_{ist} \right)$$

$$subject \quad to:$$

$$\sum_{j,t} X_{ijt} \le Q_{it} (1 - a_{ist}) \quad \forall\, i \in I \quad \forall s \in S \quad \forall\, t \in T \tag{1}$$

$$\sum_{k,t} Y_{jkt} \le P_{jt} \left(1 - a1_{jst} \right) \quad \forall\, j < m \quad \forall s \in S \quad \forall\, t \in T \tag{2}$$

$$\sum_{k,t} Y_{jkt} \le P_{jt} z_{jt} \qquad \forall\, k \in K \quad \forall\, j = m \qquad \forall\, t \in T \tag{3}$$

$$\sum_{j,t} Y_{jkt} \le d_{kt} \qquad \forall\, k \in K \quad \forall\, t \in T \tag{4}$$

$$\sum_{i,t} X_{ijt} \le P_{jt} z_{jt} \qquad \forall\, j \in J \quad \forall\, t \in T \tag{5}$$

$$\sum_{i} X_{ijt} + Inv_{jt-1} = \sum_{k} Y_{jkt} + Inv_{jt} \qquad \forall\, j \in J \quad \forall\, t \in T \tag{6}$$

$$\sum_{i,t} w_{ijt} = 1 \qquad \forall\, j \in J \quad \forall\, t \in T \tag{7}$$

$$Vw_{ijt} \ge X_{ijt} \qquad \forall\, j \in J \quad \forall\, i \in I \quad \forall\, t \in T \tag{8}$$

$$Vz_{jt} \ge Y_{jkt} \qquad \forall\, j \in J \quad \forall\, i \in I \quad \forall\, t \in T \tag{9}$$

$$z_{jt} \le \left(1 - a1_{jst}\right) \qquad \forall\, j \in J \quad \forall s \in S \quad \forall\, t \in T \tag{10}$$

$$z_{jt+1} \le \left(1 - a1_{jst}\right) \qquad \forall\, j \in J \quad \forall s \in S \quad \forall\, t \in T \tag{11}$$

$$X_{ijt} \le V(w_{ijt}(1 - a_{ist})) \quad \forall\, i \in I \quad \forall\, j \in J \ \forall s \in S \ \forall\, t \in T \tag{12}$$

$$Y_{jkt} \le V(z_{jt}(1 - a1_{jst})) \quad \forall\, j \in J \quad \forall\, k \in K \quad \forall s \in S \quad \forall\, t \in T \tag{13}$$

$$X_{ijt} \ge 0 \qquad \forall\, i \in I \quad \forall\, j \in J \quad \forall\, t \in T \tag{14}$$

$$Y_{jkt} \ge 0 \qquad \forall\, j \in J \quad \forall\, k \in K \quad \forall\, t \in T \tag{15}$$

$$Inv_{jt} \ge 0 \qquad \forall\, j \in J \quad \forall\, t \in T \tag{16}$$

$$w_{ijt} \in \{0,1\} \qquad \forall\, i \in I \quad \forall\, j \in J \quad \forall\, t \in T \tag{17}$$

$$z_{jt} \in \{0,1\} \qquad \forall\, j \in J \quad \forall\, t \in T \tag{18}$$

- Constraint (1) implies that flow amount from each manufacturer *i* depends on the manufacturer capacity at each period *t*. In other words, flow amount must be less than or equal to manufacturer capacity with also considering disruption according scenario *s*.

- Constraint (2) denotes that flow amount from each warehouse *j* depends on the warehouse capacity at each period of time *t*. The flow amount must be less than or equal to warehouse capacity. Moreover, it must conform to disruption scenario *s*.
- Constraint (3) designates the dummy (emergency) warehouse. It is explained that dummy warehouses are not affected from disruption at each period of time *t*. They are protected. Each dummy warehouse flow amount cannot exceed its capacity.
- Constraint (4) is established for retailer not to hold excess goods from the demand at each period of time *t*. The flow amount from warehouses to each retailer cannot exceed retailer's demand.
- Constraint (5) explains that flow amount from manufacturers to each warehouse *j* cannot exceed warehouse capacity at each period of time *t*.
- Constraint (6) is the inventory balance constraint. It is formed to ensure that the inventory level from *t*-1 period of time and the flow of product from manufacturer to each warehouse at period of time *t* equals to flow of product from each warehouse to retailer at period of time *t* and excess products at period of time *t*.
- Constraint (7) means each warehouse *j* can only be served by one manufacturer at each period of time *t*.
- Constraint (8) denotes that each manufacturer should be open first to send products at each period of time *t*.

- Constraint (9) indicates that each warehouse should be open first to send products at each period of time *t*.
- Constraint (10) prevents to open warehouse if the disruption scenario occurs at each period of time *t*.
- Constraint (11) provides not to open warehouse, as recovery period of two months, if the disruption scenario occurs at each period of time *t*.
- Constraints (12) and (13) ensure not to send products for both manufacturers and warehouses if they are disrupted at time period *t*.
- Constraints (14), (15) and (16) imply nonnegativity for the decision variables X_{ijt}, Y_{jkt} and Inv_{jt} .
- Constraints (17) and (18) represent that decision variables w_{ijt} and z_{jkt} are binary variables.

Model 2 GAMS codes are denoted in Appendix B.

3.6 MULTI-PRODUCT SINGLE-PERIOD NETWORK DESIGN MODEL

The Model 3 is developed as a multi-product, single period network model. The total number of commodities is equal to *E*. Every product type is indexed as *e*. The flow direction and members are assumed to be same as in Models 1 and 2. Assumptions for Model 3 are listed below.

Assumptions

1. It is assumed that disruption only occurs on nodes not the arcs (links). Therefore disruption occurs only on manufacturer nodes or warehouse nodes.
2. Warehouse can be served by more than one manufacturer.

3. Lead time is considered to be zero.
4. Multiple products are flowing throughout the network.
5. Backlog cost does not depend on time. Backlogging cost exist only on retailer nodes.
6. There exist manufacturers, warehouses and retailers in the supply chain.
7. Goods can flow only in one direction that is from left to right. Reverse direction is not allowed.
8. Two members of the network as manufacturers and warehouses are accepted as they are different plants of the same company.
9. Dummy (emergency) network member can only be from warehouses and they are certain and determined (as which ones and their quantity). Other two members (as manufacturers or retailers) cannot be dummy member.
10. There is no obligation for serving all retailers. Since the retailers are also connected to end customers which is not indicated in our network model. Every three retailer is serving to one customer. Therefore serving from one or two retailer absence forms no problem according to customer side.

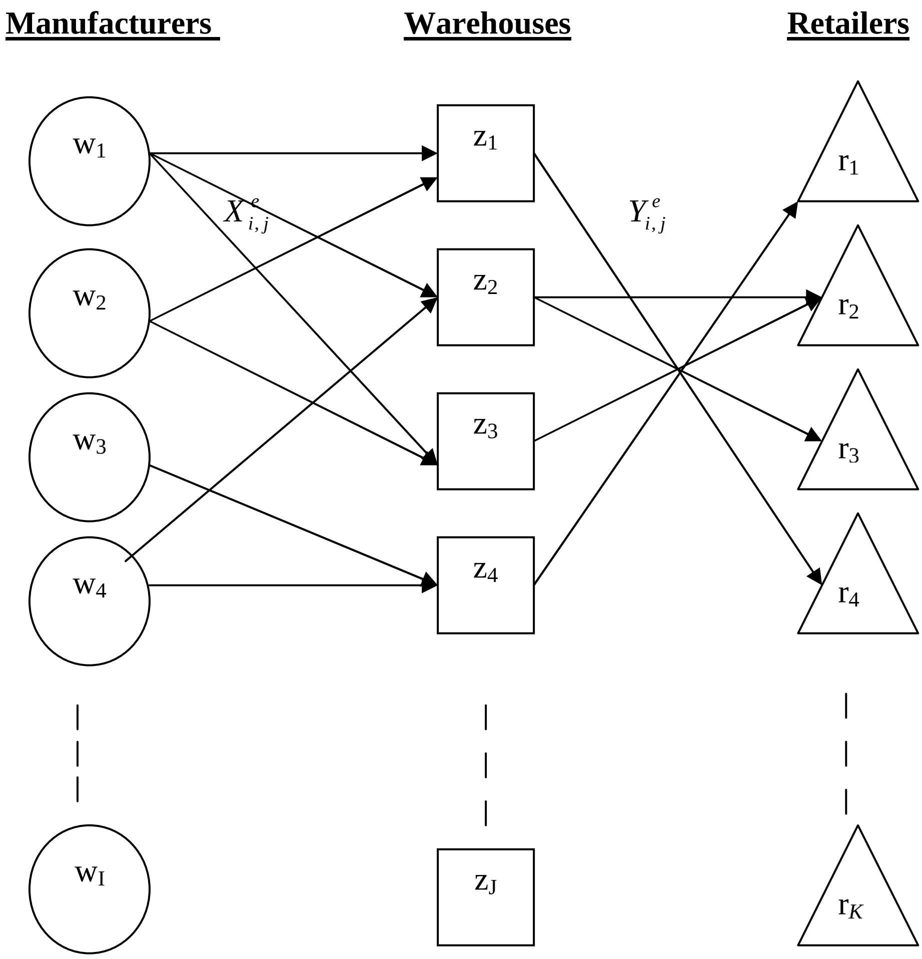


Figure 11. Multi-product network model schema

Model 3 does not depend on time. Therefore, there is no inventory level or inventory holding cost at each warehouse. Also, there is no recovery period at each warehouse as two months like in Model 2. Figure 11 indicates the supply chain network used in this model. Each warehouse can only be served by one manufacturer rule is not valid in Model 3, since products are now in variety there is no one type of product flowing throughout the network. Other assumptions stay the same as in Model 1. Additional decision variables and parameters are listed below; the other variables and input parameters are same as the ones in Model 1.

Notation

e: Each product type index

E: Total number of product types

X_{ij}^{e}*:* Number of products flow from manufacturer *i* to warehouse *j* of type *e.*

Y_{ij}^{e}*:* Number of products flow from warehouse *j* to retailer *k* of type *e.*

Q_{i}^{e}*:* Units of supply from manufacturer of type *e* product at node *i.*

P_{j}^{e}*:* Units of storage capacity of warehouse at node *j* of type *e* products.

d_{k}^{e}*:* Units of demand of retailer of type *e* products.

M_{i}^{e}*:* Unit manufacturing cost of every type product indexed as *e* at manufacturer node *i*

3.7 MATHEMATICAL FORMULATION OF MULTI-PRODUCT SINGLE-PERIOD NETWORK DESIGN MODEL

In this section we present the multi-product model to calculate the expected supply chain risk exposure in the case of a multiple products. Based on the assumptions and notation given above, Model 3 is presented below.

Model 3:

$$Minimize \sum_{i,j,e} M_{i}^{e} X_{ij}^{e} + \sum_{i,j,e} g1_{ij} X_{ij}^{e} + \sum_{j,k,e} g2_{jk} Y_{jk}^{e} + \sum_{m}^{M} f_{j} z_{j} +$$

$$\sum_{j,k,e} b_{k}\left(d_{k}^{e} - Y_{jk}^{e}\right) + \sum_{j,k,s,i} U_{jk}\left(a1_{js} + a_{is}\right)$$

$$Subject \quad to:$$

$$\sum_{j,e} X_{ij}^{e} \leq \sum_{e} Q_{i}^{e}\left(1 - a_{is}\right) \qquad \forall i \in I \qquad \forall s \in S \tag{1}$$

$$\sum_{k,e} Y_{jk}^{e} \leq \sum_{e} P_{j}^{e}\left(1 - a1_{js}\right) \qquad j < m \qquad \forall j \in J \qquad \forall s \in S \tag{2}$$

$$\sum_{k,e} Y_{jk}^{e} \leq \sum_{e} P_{j}^{e} z_{j} \qquad \forall k \in K \qquad (3)$$

$$\sum_{j,e} Y_{jk}^{e} \leq \sum_{e} d_{k}^{e} \qquad \forall k \in K \qquad (4)$$

$$\sum_{i,e} X_{ij}^{e} \leq \sum_{e} P_{j}^{e} z_{j} \qquad \forall j \in J \qquad (5)$$

$$\sum_{i,e} X_{ij}^{e} = \sum_{k,e} Y_{jk}^{e} \qquad \forall j \in J \qquad (6)$$

$$X_{ij}^{e} \leq V w_{ij} \qquad \forall i \in I \quad \forall j \in J \quad \forall e \in E \qquad (8)$$

$$Y_{ij}^{e} \leq V z_{j} \qquad \forall i \in I \quad \forall j \in J \quad \forall e \in E \qquad (9)$$

$$z_{j} \leq \left(1 - a1_{js}\right) \qquad \forall j \in J \quad \forall s \in S \qquad (10)$$

$$X_{ij}^{e} \geq 0 \qquad \forall i \in I \quad \forall j \in J \quad \forall e \in E \qquad (11)$$

$$Y_{ij}^{e} \geq 0 \qquad \forall i \in I \quad \forall j \in J \quad \forall e \in E \qquad (12)$$

$$w_{ij} \in \{0,1\} \qquad \forall i \in I \quad \forall j \in J \qquad (13)$$

$$z_{j} \in \{0,1\} \qquad \forall j \in J \quad \forall k \in K \qquad (14)$$

In multi-product model, the objective function and constraints have the same meaning. However, there is no inventory holding cost minimization in the objective function because it is assumed that Model 3 does not depend on time. Besides, there is no inventory level in each warehouse. All coming product types are all sent with no delay or holding. The lead time is zero same as other two models. The difference is the flow types of products. Other difference is the absence of constraint (7) in single-product single-period model. This means there is no obligation for each warehouse *j* to be served by one manufacturer *i*. This model is in complex supply chain models. In real life, one can encounter many examples of multi-product supply chain networks.

3.8 EXPECTED RISK EXPOSURE COMPUTATION FOR ALL MODELS

Hanna and Skipper [39] evaluate minimum risk exposure in the supply chain disruptions. Firstly, authors gather strategic actions to struggle disruptions on supply chain. Then, they count items that are affected by this strategy. They make factor analysis and give weights (in their study they define weights of "Cronbach"). Lastly, they add the weighted values. Authors compare this value with their ten defined hypothesis.

In our thesis, for scenarios a_{is} and a_{js}, their occurrence for all manufacturers and warehouses are assigned to a number. Every number symbolizes scenario integrity. In other words, if warehouse *j* is assigned the value of 1 under scenario *s*, that means warehouse *j* is disrupted. For each scenario, there is a probability of occurrence and this is determined by expert opinions and complex analysis. In this study, all scenario parameters are created randomly.

To denote the probability of occurrence for each scenario, we use the same notation used by Ross [41]. For the discrete random variable *a* the corresponding probability mass function is denoted by *p*(*a*), which is explained as below:

$$p(a) = P\{\Omega = a\}$$

The probability mass function is positive at most countable values of *a*. Ω must be assigned to these values as:

$$p(\Omega_i) \geq 0 \qquad i = 1,2,3,\ldots$$

$$p(\Omega) = 0 \qquad \text{all other values of } x$$

Table 2. Probability mass function value according to scenario *s* occurrence with probability realization $P(\omega_s)$

Probability mass function	**The scenario's value**	**Probabillity of realization** $P(\omega_s)$
$P\{\Omega = s\}$	1	0,05
$P\{\Omega = s\}$	2	0,11
$P\{\Omega = s\}$	3	0,03
$P\{\Omega = s\}$	4	0,21
$P\{\Omega = s\}$	5	0,09
$P\{\Omega = s\}$	6	0,18
$P\{\Omega = s\}$	7	0,05
$P\{\Omega = s\}$	8	0,06
$P\{\Omega = s\}$	9	0,08
$P\{\Omega = s\}$	10	0,14

For Models 1,2 and 3, we use the probability mass function given in Table 2.

$\sum_{\Omega=1}^{\infty} p(\Omega_i) = 1$ for every Ω_i values.

The probabilities are added with the one after and the cumulative distribution function is obtained as in Table 3.

Table 3. The values of cumulative distribution function and range of scenarios

Cumulative distribution function, F(s)	Range of the scenario
0	s<1
0,05	s<2
0,16	s<3
0,19	s<4
0,4	s<5
0,49	s<6
0,67	s<7
0,72	s<8
0,78	s<9
0,86	s<10
1	

Considering every scenario, with its occurrence probability, Expected Supply Chain Disruption Cost (ESCDC) or the Expected Risk Exposure value is calculated. Expected cost function formula is as follows:

$$\text{ESCDC} = \sum_{w_s, s}^{S} TC_s * P(\omega_s)$$

For the above example, the summation will be limited to 10 scenarios because the total number of scenarios is fixed to 10. According to ESCDC different supply chain strategies could be established.

CHAPTER 4

NUMERICAL RESULTS AND DISCUSSION OF THE MODELS

In this chapter, we present the numerical results for Models 1 and 2 and discuss the results. Note that GAMS 22.5 is selected as an optimization computer program. GAMS produces optimal solution and the processing time of the computer for every run. For Model 1 and Model 2 every run quantity is same as 10. Model 2 parameters are more than Model 1 because period of time parameter *t* is added. For Model 1 and Model 2 applied parameter values are determined randomly.

4.1 PARAMETERS FOR THE MODELS

Before running GAMS, determined parameters are given in the tables below. In our study, there are 9 manufacturers, 7 warehouses, 7 retailers and 10 scenarios. For each supply chain all cost parameters, capacities and demand values are listed in the following tables.

Table 4. List of manufacturers

List of Manufacturers
i1
i2
i3
i4
i5
i6
i7
i8
i9

Table 5. List of warehouses

List of warehouses
j1
j2
j3
j4
j5
j6
j7

Table 4, 5, 6 and 7 are indices used for all models.

Table 6. List of retailers

List of retailers
k1
k2
k3
k4
k5
k6
k7

Table 7. List of scenarios

List of scenarios
s1
s2
s3
s4
s5
s6
s7
s8
s9
s10

4.2 PARAMETERS FOR MODEL 1

Attained values for parameters for Model 1 are indicated in the tables below:

Table 8. Quantity and value of backlog costs at each retailer

b(k) Backlog cost of retailer at node k	
k1	50
k2	65
k3	55
k4	40
k5	30
k6	25
k7	15

Backlogging cost is considered in two digit numbers. The difference between the smallest and the biggest backlogging cost is 50.

Table 9. Manufacturer's total number and supply units

Manufacturer supply units Q_i at node i	
i1	470000
i2	425000
i3	300000
i4	410000
i5	600000
i6	650000
i7	436000
i8	400000
i9	370000

The largest parameter values are attained to manufacturer supply units as six digits.

Table 10. Capacity of warehouse at node *j*

P(j) capacity of warehouse at node j	
j1	6900
j2	6700
j3	8400
j4	8500
j5	4000
j6	5000
j7	8000

While comparing with table 10 and table 11, capacity of warehouses are assumed to be bigger than retailer demand units.

Table 11. Retailer demand units

d(k) units of demand from retailer at node k	
k1	3000
k2	4500
k3	3000
k4	2780
k5	3700
k6	5000
k7	4500

Table 12. Fixed cost of opening new emergency (dummy) facility

f(j) fixed cost of new opened dummy(emergency) facility	
1	0
2	0
3	0
4	0
5	100000
6	150000
7	170000

Fixed costs only occur on emergency (dummy) warehouses because they are the protection nodes for system to prevent disruption on product flows. Last three warehouse nodes as 5, 6 and 7 are assumed to be emergency (dummy) warehouse.

Table 13. Trust reduction cost in retailer *k* according to warehouse *j*

U(j,k) trust reduction cost at node k	k1	k2	k3	k4	k5	k6	k7
j1	35	27	30	33	26	23	32
j2	24	21	37	34	39	25	22
j3	36	31	28	39	41	20	43
j4	45	24	35	37	22	38	25
j5	21	40	39	37	26	33	31
j6	25	15	43	39	28	23	25
j7	26	27	45	17	37	16	35

Trust reduction values appear on only retailers for not to be sent by warehouses.

Trust reduction costs are considered to be two digit numbers.

Table 14. Occurrence of scenario *s* binary value on manufacturer

a(s,i) scenario s occurence value on manufacturer node i	i1	i2	i3	i4	i5	i6	i7	i8	i9
s1	0	0	1	0	0	0	0	0	0
s2	0	0	0	0	1	0	0	1	0
s3	1	0	0	0	0	0	1	0	0
s4	0	0	0	1	0	0	0	0	1
s5	0	0	0	0	0	1	0	1	0
s6	0	1	0	0	0	0	1	0	0
s7	0	0	1	0	1	0	0	0	0
s8	0	0	0	1	0	0	1	0	0
s9	1	0	0	0	0	1	0	0	0
s10	0	1	0	0	0	0	0	0	1

Disruption scenarios for both manufacturers and warehouses occur randomly and independently with each other. Whether according to the same disruption one or more manufacturer or warehouse can be affected.

Table 15. Occurrence of scenario *s* binary value on warehouse

a1(s,j) scenario s occurence value on warehouse node j	j1	j2	j3	j4	j5 (dummy)	j6 (dummy)	j7 (dummy)
s1	0	1	0	0	0	0	0
s2	0	0	1	0	0	0	0
s3	0	0	0	1	0	0	0
s4	0	1	0	0	0	0	0
s5	0	0	1	0	0	0	0
s6	1	0	0	1	0	0	0
s7	0	1	1	0	0	0	0
s8	0	0	0	1	0	0	0
s9	0	0	1	0	0	0	0
s10	1	1	0	0	0	0	0

Table 16. Transportation cost from each manufacturer node to each warehouse node

t(i,j) distance from manufacturer node i to warehouse node j	i1	i2	i3	i4	i5	i6	i7	i8	i9
j1	10	8	2	11	7	5	4	9	3
j2	2	3	4	8	5	9	11	3	12
j3	5	4	11	2	3	6	7	10	9
j4	12	11	7	5	9	15	3	6	4
j5	3	5	8	6	2	9	10	4	7
j6	8	6	5	3	4	7	9	11	2
j7	4	2	6	7	10	3	5	8	11

Transportation costs for manufacturer disruptions to warehouse nodes are important because they affect objective function value. They should be minimized.

Table 17. Transportation cost from each warehouse node to each retailer node

t(k,j) distance from warehouse node j to retailer node k	1	2	3	4	5	6	7
k1	8	2	5	6	4	2	11
k2	7	3	9	2	5	4	8
k3	5	7	2	3	6	8	4
k4	4	6	3	4	2	5	7
k5	11	8	4	7	3	6	2
k6	2	4	6	5	7	3	9
k7	6	5	7	4	10	2	3

Transportation costs of warehouse nodes to retailer nodes are also important because they affect objective function value like other transportation cost. They should be minimized.

4.3 PARAMETERS FOR MODEL 2

Attained values for parameters for model 2 are indicated in the tables below:

Table 18. Values of backlog costs

b(k,t)	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
k1	50	40	32	25	17	27	18	51	37	19	47	18
k2	65	37	51	54	21	18	46	34	44	27	17	57
k3	55	24	45	36	31	37	55	17	50	33	56	44
k4	40	19	27	43	52	43	31	22	16	49	39	32
k5	30	33	37	38	44	51	26	46	31	52	24	26
k6	25	29	19	49	35	25	47	21	48	37	32	38
k7	15	41	37	20	45	35	30	38	28	24	43	17

Backlog costs for Model 2 are all period of time dependent. Time periods are divided for all parameters are same as 12 months of one year. The numbers are constituted by two digits same as Model 1.

Table 19. Values of inventory holding costs

h(j,t)	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
j1	0	0	0	7	0	0	11	0	0	5	0	0
j2	0	6	0	0	0	0	0	0	0	0	8	0
j3	0	0	0	0	9	0	0	0	0	0	0	0
j4	0	0	0	4	0	17	0	0	0	0	0	20
j5	0	0	7	0	11	15	0	0	9	0	0	15
j6	0	0	0	0	0	0	0	0	0	0	0	0
j7	0	0	0	0	0	0	0	0	0	0	0	0

Inventory holding cost in Model 2 sometimes zero because the value of holding decreased in the way of product currency value decreased.

Table 20. Manufacturing costs

E(i,t) t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
i1	20	30	35	25	27	40	33	23	25	35	40	21
i2	33	21	15	24	28	36	21	38	18	39	25	27
i3	15	26	22	31	29	17	40	31	35	17	19	24
i4	30	16	14	19	2	25	33	28	34	19	23	28
i5	17	19	20	34	19	22	27	15	30	24	14	35
i6	34	12	28	16	29	30	22	27	11	36	24	31
i7	14	20	15	22	30	19	17	25	22	30	33	18
i8	20	26	27	23	16	31	28	30	18	21	15	28
i9	29	19	17	20	15	26	14	22	18	23	27	16

Manufacturing cost is a new type of cost occurred in Model 2. In Model 1 there assumed no manufacturing cost.

Table 21. Manufacturer's total supply units (in 10000)

Q(i,t) t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
i1	47	45	51	64	53	47	56	47	35	68	37	75
i2	42,5	35	48	54	46	60	64	62	63	64	45	61
i3	30	50	43	47	34	58	45	39	58	44	65	37
i4	41	47	61	61	59	55	41	53	48	75	56	74
i5	60	35	59	39	73	34	37	57	61	51	38	55
i6	65	41	38	49	55	45	57	64	55	37	49	62
i7	43,6	48	63	50	70	63	48	44	62	48	61	71
i8	40	60	45	76	38	75	61	56	64	56	67	58
i9	37	64	46	51	43	59	39	55	59	61	34	77

Manufacturers supply units is bigger than other parameters like in Model 1. There is no inventory holding or backlogging cost at manufacturer nodes as denoted above.

Table 22. Capacity of warehouses

P(j,t) capacity of ware. at node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
j1	6900	8400	5700	4300	5700	4400	5300	8400	8500	7900	5900	8100
j2	6700	7500	8100	5100	8000	6300	8200	4200	6100	8200	8100	5800
j3	8400	8100	7200	8600	7200	8400	7900	5100	8200	5900	7800	8800
j4	8500	6100	8500	6700	4900	8200	5900	6300	4600	8300	8500	8400
j5	4000	7400	8700	8000	6200	8000	5600	8100	5900	8000	7000	4900
j6	5000	8100	6800	8100	8200	8100	8500	6500	8100	5500	8100	7100
j7	8000	6400	7500	8500	6100	5700	8400	8300	6800	8200	8300	7100

Model 2 is concerning multi-period in all decision variables and most of the parameters. Capacity of warehouses and retailer demand units are also depend on period of time t.

Table 23. Retailer demand units

d(k,t) units of demand from retailer at node k at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
k1	3000	4100	2500	3000	4000	2000	3000	4000	2300	2700	3300	2400
k2	4500	3200	3000	2400	2000	3000	2600	2000	2900	3500	2000	2700
k3	3000	2200	4500	2700	3000	2100	2200	3200	2800	4100	1900	2100
k4	2780	3500	2100	2800	2100	2900	2500	2100	2500	2000	3600	2000
k5	3700	4000	3200	2000	2700	3100	2000	2200	3700	1800	2400	3100
k6	5000	2100	1700	4000	2500	1800	3300	2400	3100	1700	2100	3000
k7	4500	3400	1200	2900	2300	2400	1200	2300	4000	2300	2100	1400

Table 24. Fixed cost of opening new emergency (dummy) facility

f(j)	
j1	0
j2	0
j3	0
j4	0
j5	100000
j6	150000
j7	170000

Fixed cost values in Model 2 are considered to be same as in Model 1.

Table 25. Trust reduction cost in retailer *k* according to warehouse *j*

U(j,k) trust reduction cost at node k	k1	k2	k3	k4	k5	k6	k7
1	35	27	30	33	26	23	32
2	24	21	37	34	39	25	22
3	36	31	28	39	41	20	43
4	45	24	35	37	22	38	25
5	21	40	39	37	26	33	31
6	25	15	43	39	28	23	25
7	26	27	45	17	37	16	35

Trust reduction cost values are considered to be digit numbered values same as in Model 1.

<u>Occurrences of the scenarios on manufacturers</u>

Table 26. Model 1's 1st scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s1.i1	0	0	0	0	0	0	0	0	0	0	1	1
s1.i2	1	1	0	0	0	0	0	0	0	0	0	0
s1.i3	0	1	1	1	0	0	0	0	0	0	0	0
s1.i4	0	0	0	0	1	1	0	0	0	0	0	0
s1.i5	0	0	0	0	0	0	0	0	1	1	0	0
s1.i6	0	0	0	0	0	1	1	0	0	0	0	0
s1.i7	0	0	1	0	0	0	0	0	0	0	0	0
s1.i8	0	0	0	0	1	0	0	0	0	0	0	0
s1.i9	0	0	0	0	0	0	1	1	0	0	0	0

In model two manufacturer scenarios are all depend on time. They occur randomly and independently.

Table 27. Model 1's 2 nd scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s2.i1	0	1	1	0	0	0	0	0	0	0	0	0
s2.i2	0	0	0	1	1	0	0	0	0	0	0	0
s2.i3	0	0	0	0	0	0	0	1	1	0	0	0
s2.i4	0	0	0	0	1	1	0	0	0	0	0	0
s2.i5	0	1	1	0	0	0	0	0	0	0	0	0
s2.i6	0	0	0	0	1	0	0	0	0	0	0	0
s2.i7	0	1	1	1	0	0	0	0	0	0	0	0
s2.i8	0	0	0	0	0	0	1	1	0	0	0	0
s2.i9	0	0	0	0	0	0	0	0	1	1	0	0

Table 28. Model 1's 3rd scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s3.i1	1	1	0	0	0	0	0	0	0	0	0	0
s3.i2	0	0	1	1	0	0	0	0	0	0	0	0
s3.i3	0	0	0	0	1	1	0	0	0	0	0	0
s3.i4	0	0	0	0	0	0	0	0	0	1	1	1
s3.i5	0	0	1	1	0	0	0	0	0	0	0	0
s3.i6	0	0	0	0	0	0	1	1	0	0	0	0
s3.i7	0	0	0	0	1	1	0	0	0	0	0	0
s3.i8	0	0	0	0	0	0	0	1	1	0	0	0
s3.i9	0	1	1	0	0	0	0	0	0	0	0	0

There are ten scenarios in Model 2 same as in Model 1.

Table 29. Model 1's 4th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s4.i1	0	0	0	0	1	1	0	0	0	0	0	0
s4.i2	1	1	0	0	0	0	1	0	0	0	0	0
s4.i3	0	0	0	0	0	0	0	0	0	1	1	0
s4.i4	0	0	0	0	0	0	0	1	1	0	0	0
s4.i5	0	0	0	1	1	1	0	0	0	0	0	0
s4.i6	0	0	0	0	0	0	1	1	0	0	0	0
s4.i7	0	0	0	0	0	0	0	0	0	1	1	0
s4.i8	0	0	0	0	0	0	1	1	0	0	0	0
s4.i9	0	0	0	1	1	0	0	0	0	0	0	0

For the 4th scenario of manufacturers no disruption occurs at t12 as last month of the year.

Table 30. Model 1's 5th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s5.i1	0	0	0	0	0	1	1	0	0	0	0	0
s5.i2	0	0	0	0	0	0	0	0	1	1	1	0
s5.i3	0	1	1	0	0	0	0	0	0	0	0	0
s5.i4	0	0	0	1	0	0	0	0	0	0	0	0
s5.i5	0	0	0	0	0	0	0	1	0	0	0	0
s5.i6	0	0	0	0	1	1	0	0	0	0	0	0
s5.i7	1	0	0	0	0	0	0	0	0	0	0	0
s5.i8	0	0	0	0	0	0	0	0	1	1	0	0
s5.i9	0	0	1	1	0	0	0	0	0	0	0	0

For the 5th scenario of manufacturers no disruption occurs at t12 as last month of the year same as in 4th scenario.

Table 31. Model 1's 6th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s6.i1	0	0	0	0	1	0	0	0	0	0	0	0
s6.i2	0	0	0	1	1	0	0	0	0	0	0	0
s6.i3	0	0	0	0	0	0	0	1	1	0	0	0
s6.i4	0	0	0	0	1	1	0	0	0	0	0	0
s6.i5	0	0	0	0	0	0	0	0	0	0	1	1
s6.i6	0	0	0	0	0	1	1	0	0	0	0	0
s6.i7	0	0	0	0	0	0	0	1	1	1	0	0
s6.i8	0	0	0	0	1	1	1	0	0	0	0	0
s6.i9	0	0	0	1	0	0	0	0	0	0	0	0

In period of times t1 and t2 no disruption occurs for the 6th scenario for manufacturer disruptions.

Table 32. Model 1's 7th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s7.i1	0	0	0	0	0	0	0	0	0	1	1	1
s7.i2	0	0	0	0	0	0	1	0	0	0	0	0
s7.i3	0	0	0	0	1	0	0	0	0	0	0	0
s7.i4	0	1	1	0	0	0	0	0	0	0	0	0
s7.i5	0	0	0	0	0	0	0	1	1	0	0	0
s7.i6	0	0	0	0	1	1	0	0	0	0	0	0
s7.i7	0	0	0	0	0	0	0	0	0	1	0	0
s7.i8	0	0	0	0	0	0	1	0	0	0	0	0
s7.i9	1	1	0	0	0	0	0	0	0	0	0	0

For the 7th scenario disruption occurs at first manufacturer node in periods of time t10, t11 and t12 consecutively.

Table 33. Model 1's 8th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s8.i1	0	0	0	0	0	1	1	0	0	0	0	0
s8.i2	0	0	0	0	0	0	0	1	1	0	0	0
s8.i3	0	1	1	1	0	0	0	0	0	0	0	0
s8.i4	0	0	0	0	0	0	1	1	0	0	0	0
s8.i5	1	1	0	0	0	0	0	0	0	0	0	0
s8.i6	0	0	0	1	1	0	0	0	0	0	0	0
s8.i7	0	0	0	0	0	0	0	0	0	0	1	0
s8.i8	1	1	0	0	0	0	0	0	0	0	0	0
s8.i9	0	0	0	0	0	0	0	1	1	1	0	0

For the 8th scenario all disruptions at manufacturers occur consecutively in two periods of time except the 7th and 9th manufacturer. Disruption occurs at one period of time at 7th manufacturer and disruption occurs at three period of time at 9th manufacturer.

Table 34. Model 1's 9th scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s9.i1	0	0	0	0	1	0	0	0	0	0	0	0
s9.i2	0	0	0	0	0	0	1	0	0	0	0	0
s9.i3	0	0	0	0	0	1	0	0	0	0	0	0
s9.i4	0	0	0	0	0	0	0	1	1	1	0	0
s9.i5	0	0	0	0	0	0	0	0	0	1	1	0
s9.i6	0	1	1	0	0	0	0	0	0	0	0	0
s9.i7	0	0	0	0	1	1	0	0	0	0	0	0
s9.i8	0	0	0	0	0	0	0	1	1	0	0	0
s9.i9	0	0	0	0	0	1	1	0	0	0	0	0

For the 9th scenario no disruption occurs at period of time t1.

Table 35. Model 1's 10^{th} scenario for manufacturer disruptions

a(s,i,t) scenario s occurrence value on manufacturer node i at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s10.i1	0	0	0	0	0	0	0	1	0	0	0	0
s10.i2	0	0	0	0	1	1	1	0	0	0	0	0
s10.i3	0	1	1	0	0	0	0	0	0	0	0	0
s10.i4	0	0	0	1	0	0	0	0	0	0	0	0
s10.i5	0	0	0	0	0	0	0	0	0	0	1	1
s10.i6	0	0	0	0	0	0	1	1	0	0	0	0
s10.i7	0	0	1	1	0	0	0	0	0	0	0	0
s10.i8	0	0	0	0	0	1	1	1	0	0	0	0
s10.i9	0	1	1	0	0	0	0	0	0	0	0	0

For the 9^{th} scenario no disruption occurs at period of time t10. Disruptions for manufacturer 5 occur at last two periods as t11 and t12.

Occurrences of the scenarios on warehouses

Table 36. Model 2's 1^{st} scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s1.j1	0	1	1	0	0	0	0	0	0	0	0	0
s1.j2	0	0	1	1	1	0	0	0	0	0	0	1
s1.j3	0	0	0	0	1	1	0	0	0	0	0	0
s1.j4	0	0	0	0	0	0	0	1	1	0	0	0
s1.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s1.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s1.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

As can be seen in table 36 in periods of time t1, t9 and t10 no disruption occurs at warehouses.

Table 37. Model 2's 2nd scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s2.j1	0	0	1	1	0	0	0	0	0	0	0	0
s2.j2	0	1	1	0	0	0	0	0	0	0	0	0
s2.j3	0	0	0	0	0	0	0	0	1	1	0	0
s2.j4	0	0	0	1	1	1	0	0	0	0	0	0
s2.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s2.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s2.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

Table 38. Model 2's 3rd scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s3.j1	0	0	0	0	0	0	1	1	1	0	0	0
s3.j2	0	0	0	1	1	0	0	0	0	0	0	0
s3.j3	0	0	0	0	0	0	0	0	0	0	1	1
s3.j4	0	0	1	1	0	0	0	0	0	0	0	0
s3.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s3.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s3.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

As explained below, every period of time no disruption occurs in emergency (dummy) warehouses.

Table 39. Model 2's 4th scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s4.j1	0	0	0	0	0	0	0	0	0	1	1	0
s4.j2	0	1	1	1	0	0	0	0	0	0	0	0
s4.j3	0	0	0	0	0	1	1	0	0	0	0	0
s4.j4	0	0	0	0	0	0	0	1	1	0	0	0
s4.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s4.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s4.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

Table 40. Model 2's 5th scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s5.j1	0	0	0	1	1	0	0	0	0	0	0	0
s5.j2	0	1	1	1	0	0	0	0	0	0	0	0
s5.j3	0	0	0	0	0	1	1	0	0	0	0	0
s5.j4	0	0	0	0	0	0	0	1	1	0	0	0
s5.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s5.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s5.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

For the 2nd warehouse disruption occur for three periods of time as t2, t3 and t4 consecutively.

Table 41. Model 2's 6th scenario for warehouse disruptions

a1(s,j,t) scenario s occurence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s6.j1	0	0	0	0	0	0	0	1	1	0	0	0
s6.j2	0	0	0	0	0	1	0	0	0	0	0	0
s6.j3	0	0	0	1	1	1	0	0	0	0	0	0
s6.j4	0	0	0	0	0	0	0	0	0	0	1	1
s6.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s6.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s6.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

Table 42 Model 2's 7th scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s7.j1	0	0	0	0	1	1	0	0	0	0	0	0
s7.j2	0	1	0	0	0	0	0	0	0	0	0	0
s7.j3	0	0	1	1	1	0	0	0	0	0	0	0
s7.j4	0	0	0	0	0	0	0	0	0	1	1	0
s7.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s7.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s7.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

In 7th scenario no disruption occurs in periods t7, t8 and t9.

Table 43. Model 2's 8th scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s8.j1	0	0	0	1	0	0	0	0	0	0	0	0
s8.2	0	0	0	0	0	0	0	1	0	0	0	0
s8.j3	0	0	0	0	0	0	1	1	1	0	0	0
s8.j4	1	1	0	0	0	0	0	0	0	0	0	0
s8.j5 dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s8.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s8.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

In 8th scenario some periods of time do not have disruption. These are t3, t5, t6, t10 and t11.

Table 44. Model 2's 9th scenario for warehouse disruptions

a1(s,j,t) scenario s occurrence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s9.j1	0	0	0	0	1	0	0	0	0	0	0	0
s9.2	0	0	0	0	0	0	0	0	0	0	0	1
s9.j3	0	0	0	0	0	0	0	0	1	1	0	0
s9.j4	0	0	0	1	1	0	0	0	0	0	0	0
s9.j5 dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s9.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s9.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

In 9th scenario, at warehouse 2, disruption occurs at the last period of time, t12.

Table 45. Model 2's 10th scenario for warehouse disruptions

a1(s,j,t) scenario s occurence value on warehouse node j at period of time t	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
s10.j1	0	0	0	0	0	0	0	1	0	0	0	0
s10.j2	0	0	0	0	0	1	1	0	0	0	0	0
s10.j3	0	0	0	0	0	0	0	0	1	1	0	0
s10.j4	0	0	0	1	1	0	0	0	0	0	0	0
s10.j5 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s10.j6 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0
s10.j7 (dummy)	0	0	0	0	0	0	0	0	0	0	0	0

In 10th scenario all disruption occurs two periods of time consecutively except in period of time t8.

Table 46. Transportation cost from each manufacturer node to each warehouse node

g1(j,i) distance from manufacturer node i to warehouse node j	i1	i2	i3	i4	i5	i6	i7	i8	i9
j1	11	8	20	4	7	23	4	22	15
j2	2	3	4	8	5	9	11	3	12
j3	5	4	11	2	3	6	7	10	9
j4	12	11	7	5	9	15	3	6	4
j5	3	5	8	24	2	9	10	4	7
j6	8	20	5	3	4	7	9	11	2
j7	4	2	25	7	10	16	14	8	11

Both in Tables 46 and 47 the transportation costs are assumed as two digit numbers.

Table 47. Transportation cost from each warehouse node to each retailer node

g2(k,j) distance from warehouse node j to retailer node k	j1	j2	j3	j4	j5	j6	j7
k1	8	2	12	6	4	2	11
k2	7	3	9	2	12	4	8
k3	5	7	2	3	6	22	4
k4	4	6	3	4	21	1	7
k5	6	20	4	11	3	6	2
k6	2	15	6	5	7	11	9
k7	3	5	7	4	1	2	3

Running the single-product supply chain network model in GAMS has table solution for every scenario s. There are ten scenarios in our model which is denoted before. For the first scenario as a_{ist} and $a1_{jst}$, decision variables values X_{ijt}, Y_{jkt}, z_{jt} and w_{ijt} after running GAMS are indicating the results. GAMS indicates which manufacturer and warehouse should be opened, what is the flow amount between each manufacturer to each warehouse, what is the flow amount between each warehouse to each retailer and the inventory level at each warehouse.

For first scenario s1 the results for both Model 1 and Model 2 are shown in the tables below:

4.4 RESULTS OF MODEL 1

Results for the first scenario of single-product single-period model in GAMS are designated below:

Table 48. Model 1 flow values from manufacturer to warehouse

X_{ij}	j4	j5	j6	j7
i2				8000
i5		4000		
i7	8500			
i9			5000	

Table 49. Model 1 flow values from warehouse to retailer

Y_{jk}	k1	k2	k3	k4	k5	k6	k7
j4		4500	2220			1780	
j5	1220			2780			
j6	1780					3220	
j7			780		3700		3520

Table 50. Model 1 decision variable showing each warehouse is opened or not

z_j	Open or not
4	1
5	1
6	1
7	1

Table 51. Model 1 decision variable showing each manufacturer is opened or not

w_{ij}	j1	j2	j3	j4	j5	j6	j7
i1		1	1				
i2							1
i5					1		
i7				1			
i9	1					1	

For interpreting the results, first of all it should be referred to the values of scenarios both from in manufacturer and warehouse nodes. First scenario occurrence at manufacturers denotes that third manufacturer node is disrupted. Therefore, it cannot be opened. First scenario occurrence at warehouses denotes that second warehouse is disrupted. Therefore, it cannot be opened. The results are consistent with this rule. No product is flowing from second warehouse and no product is flowing from third manufacturer.

All emergency warehouses are opened as 5, 6 and 7 to send products. Occurrence of this necessity can be emanating due to the distance cost factor or capacity of emergency warehouses. Undisrupted manufacturers sending products are first, second, fifth, seventh and nineth manufacturers. Opened warehouses to send products are forth, fifth, sixth and seventh warehouses. Note that fifth, sixth and seventh warehouses are emergency warehouses.

There is no inventory held at none of the nodes. Therefore the total inflow to each warehouse is equal to total outflow from the same warehouse. For instance, the second manufacturer sends 8000 units to the seventh warehouse. Seventh warehouse sends 780, 3700 and 3520 units (totally equal to 8000) to retailers. Besides, all demand units of retailers are satisfied by undisrupted and recently opened emergency warehouses.

4.5 RESULTS OF MODEL 2

Results for the first scenario of single-product multi-period model in GAMS are denoted below:

Table 52. Model 2 flow values from manufacturer to warehouse at each period

	t1	t2	t3	t4	t5	t6
i3.2	670					
i4.3		8100	7200	8600		
i4.4			8500	4000		
i5.1					5700	
i5.3	8400					
i7.1	6900					3100
i7.4	8500					7400
i9.4					4900	

	t7	t8	t9	t10	t11	t12
i3.2				4600		
i4.3				5900		
i5.1		8400			5100	
i5.2		4200				
i5.3		5100			7800	
i6.2			6100			
i6.3			8200			
i7.1	5300					
i7.4	5900					
i8.2						
i9.4						4900

Table 53. Model 2 flow values from warehouse to retailer at each period

	t1	t2	t3	t4	t5	t6
j1.k1	400					
j1.k2	420					
j1.k4	1080					
j1.k5					2700	3100
j1.k6	5000				2500	
j1.k7					500	
j2.k1	2600	4100				
j3.k3	3000		4000	2700		
j3.k4	1700			2800		
j3.k5	3700	4000	3200	2000		
j3.k6		1920		1100		
j3.k7		2180				
j4.k1			2500			
j4.k2	4080	3200	3000	2400		
j4.k3			500		1000	2100
j4.k4					2100	2900
j4.k6				2900		
j4.k7		1220	1200		1800	2400

	t7	t8	t9	t10	t11	t12
j1.k4	1400					
j1.k6	3300		1400	1700	2100	3000
j1.k7	600	1300	4000			
j2.k1		4000	2300		3300	
j2.k2		200	2900	3500		
j2.k4				2000	2700	
j2.k7					2100	
j3.k2		1800				
j3.k3			2800	4100	1900	
j3.k4		100			900	1900
j3.k5		2200	3700	1800		3100
j3.k6			1700			
j3.k7		1000				
j4.k2	2600					2700
j4.k3	2200					2100
j4.k4	1100					100

Table 54. Model 2 inventory level at each period of time

	t1	t3	t8	t9	t11
j1			7100	1700	3000
j2	4100			900	
j3					5000
j4	4420	1300			

Table 55. Model 2 decision variable showing each warehouse is opened or not

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12
j1					1	1	1	1	1	1	1	1
j2	1	1					1	1	1	1	1	
j3	1	1	1	1				1	1	1	1	1
j4	1	1	1	1	1	1	1				1	1

Table 56. Model 2 decision variable showing each manufacturer is opened or not

	t1	t2	t3	t4	t5	t6
i1.1		1	1	1		
i1.2		1	1	1	1	1
i1.3					1	1
i1.4		1				
i1.5	1	1	1	1	1	1
i1.6		1	1	1	1	1
i1.7	1	1	1	1	1	1
i3.2	1					
i3.6	1					
i4.3		1	1	1		
i4.4			1	1		
i5.1					1	
i5.3	1					
i7.1	1					1
i7.4	1					1
i9.4					1	

Table 56. Model 2 decision variable showing each manufacturer is opened or not (cont'd)

	t7	t8	t9	t10	t11	t12
i1.1			1	1		
i1.2	1					1
i1.3	1					
i1.4		1	1	1		
i1.5	1	1	1	1		
i1.6	1	1	1	1		
i1.7	1	1	1	1		
i2.1						1
i2.3						1
i2.4					1	
i2.5					1	1
i2.6					1	1
i2.7					1	1
i3.2				1		
i4.3				1		
i5.1		1			1	
i5.2		1				
i5.3		1			1	
i6.2			1			
i6.3			1			
i7.1	1					
i7.4	1					
i8.2					1	
i9.4						1

Model 2 decision variables depend on period of time as months of the year. In Model 2, additional manufacturing costs at manufacturers and inventory holding costs at warehouses are considered. They all effect on results.

Referring to the first scenario at manufacturers, it cannot be open first manufacturer in periods of time t11 and t12. This is satisfied by the result table 52 and table 56. Table 52 demonstrates the flow amount of manufacturers. First manufacturer does not send any products at any period of time according to first scenario. Table 56 denotes the state of manufacturers which are opened or not. First manufacturer is not opened at periods of time t11 and t12 according to first scenario.

Considering first warehouse at the first scenario; it cannot be opened at periods of time as t2, t3 and t4. Disruption occurs at two periods of time as t2 and t3. However, there is a recovery period for every warehouse after the disruption (including the disruption month). Therefore, the first warehouse cannot be opened at period of time t4. Table 53 and Table 55 satisfy this assumption. In Table 53, there is no flow from first warehouse at periods of time t2, t3 and t4. In Table 55, first warehouse is not opened (values 0) at the same periods of time.

Demand units of retailers are satisfied also. For instance, the first retailer in the first scenario demands 3000 units in period of time t1 and 4100 units in period of time t2. From the Table 53 considering the flow values of warehouses, first warehouse sends 400 units at period t1 and second warehouse sends 2600 units at the same period of time. The total amount of demand is satisfied. For the other example, the first retailer in the first scenario at period of time t2 requires 4100 units. Second warehouse satisfies this amount 4100 as can be seen in Table 52.

In Model 2, warehouses can hold inventories considering the inventory holding cost at period of times. Table 54 shows the inventory amounts at warehouses. According to the first scenario warehouse one hold inventory of 7100 at period of time t8, 1700 at t9 and 3000 units at t11. The second warehouse holds inventory of 4100 units at period of time t1 and 900 units at t9. Third warehouse hold inventory at period of time t11 with 5000 units. Forth warehouse hold inventory at period of time t1 4420 units and at t3 1300 units.

4.6 RISK EXPOSURE VALUE AS EXPECTED SUPPLY CHAIN DISRUPTION COST FOR MODEL 1

Considering all the scenarios in set *S*; the Model 1 is optimized several times. The optimal flow amounts from manufacturers to warehouses and optimal flow amounts from warehouses to retailers are obtained with the corresponding total minimum cost. Thus, for ten different scenarios, we obtain ten different objective function values, each of which corresponds to the optimal flow and optimal serving if the disruption occurs.

After running 10 scenarios, we can calculate the expected risk exposure or the expected supply chain disruption cost by the following formula.

$$\text{ESCDC} = \sum_{w_s, s}^{S} TC_s * P(\omega_s)$$

ESCDC=(6428684*0,05)+(6417562*0,11)+(6437846*0,03)+(6430522*0,21)+ (6431254*0,09)+(6435309*0,18)+(6455948*0,05)+(6431146*0,06)+ (6437954*0,08)+ (6490322*0,14) **= 6.440.427,06**

This value means a company with these amounts of manufacturers, warehouses, retailer, same constraint, same objective and the given probability of disruptions has this amount of expected risk exposure. This value is calculated according to optimality conditions. Companies can calculate their expected risk exposure value considering the past disruption occurrence data.

4.7 RISK EXPOSURE VALUE AS EXPECTED SUPPLY CHAIN DISRUPTION COST FOR MODEL 2

Same formula is used for risk exposure as expected supply chain disruption cost in Model 2.

$$\text{ESCDC} = \sum_{w_s, s}^{S} TC_s * P(\omega_s)$$

ESCDC=(54566132*0,05)+(54760230*0,11)+(54621950*0,03)+(54524134*0,21)+ (54682334*0,09)+(54577980*0,18)+(54686980*0,05)+(54666186*0,06)+ (54561924*0,08)+ (54643542*0,14) **= 44.310.774,36**

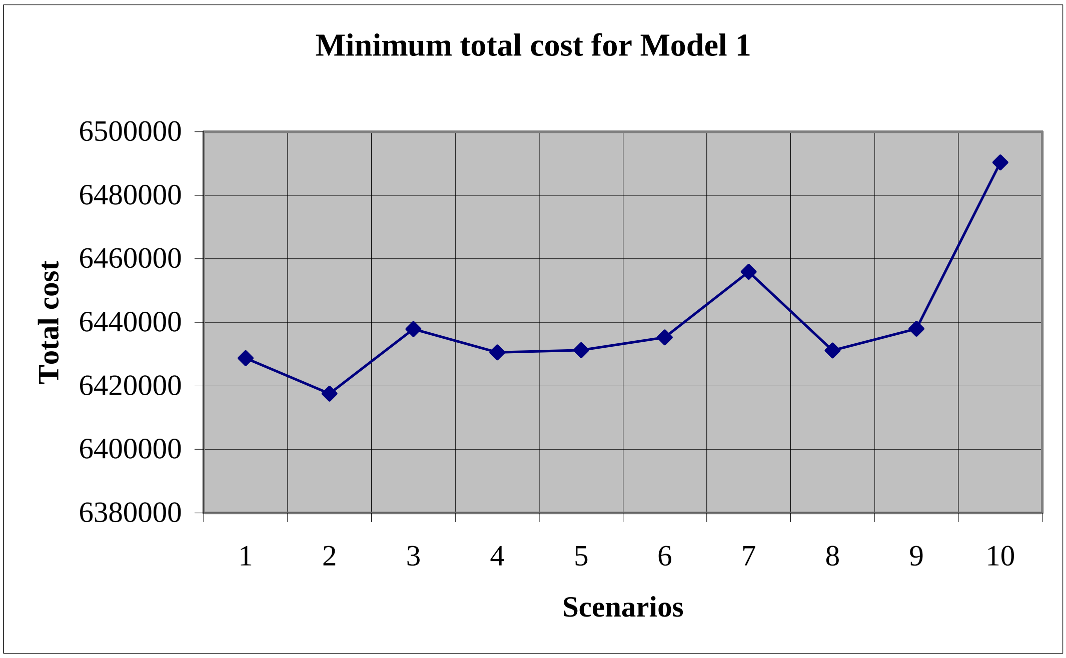
Model 2 risk exposure cost value is bigger than Model 1 because manufacturing cost and inventory holding costs are added to supply chain network. These costs increase the total optimal minimal cost level.

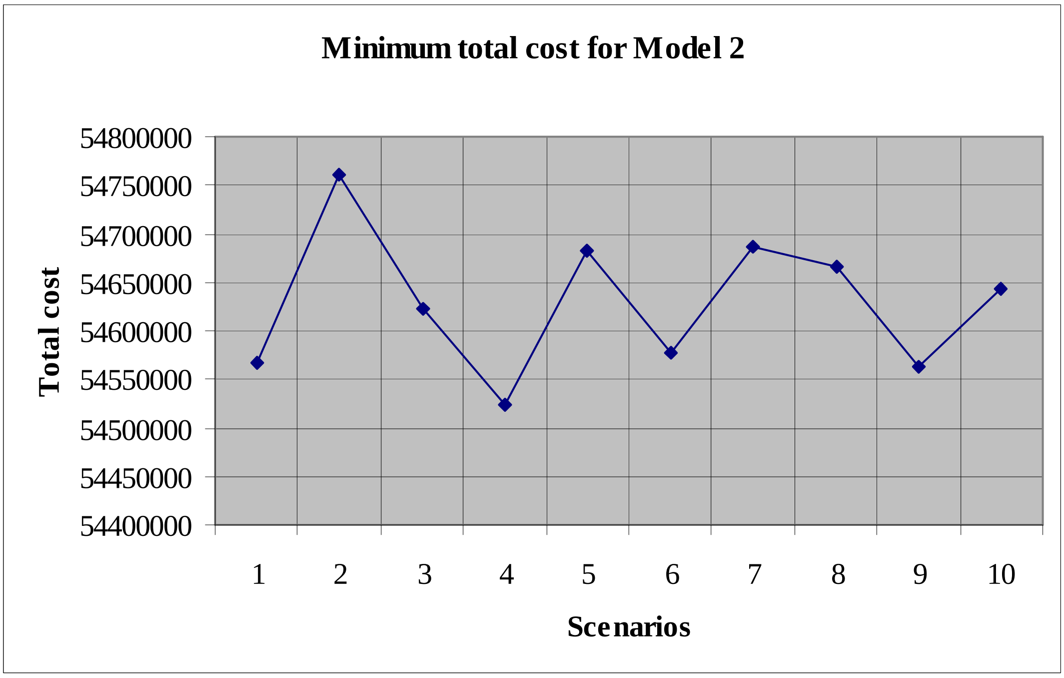
According to Figure 12, the highest total cost is observed in scenario ten for Model 1 and the highest total cost is observed in scenario two for Model 2. Generally, for both models the total cost values' differences are not high within Model 1 and Model 2. Total costs are approximately in same values within each model.

It can be perceived that there is approximately 40.000.000 cost difference between Model 2 and Model 1. The reason for the high difference is the existence of the holding and manufacturing costs in Model 2. Even one different cost type is added to the supply chain network, the optimal result is going to increase.

Two digit valued manufacturing cost and two digit valued inventory holding cost result make approximately two times increase of their multiplication digit quantity. These two cost multiplication has 4 digit values and the increase difference is 40.000.000 as 8 digit number. It is convenient to interpret that, every added cost increase the optimal total cost digit with multiplication with itself (2^{nd} exponential) digit amount.

Figure 12. Comparison of optimal costs for Model 1 and Model 2





CHAPTER 5

CONCLUSION

Managing supply chain risk is very important. Its importance increases while disruption occurs. Disruption occurrences do not depend on time, location or company. Unfortunately, it is impossible to know the exact time of occurrence, location or magnitude of the disruptions. Therefore, required precautions should be taken from companies before disruptions arise. Companies always want to cope with disruptions in the supply chain. They tend to try many ways. Some of them try to strengthen their relation with customers and suppliers through customer relationship and supplier relationship management. Relation is the key factor between the company, government and other members of the supply chain. Some companies strengthen their control on the information flow with new IT methods. Some of them establish business unit for risk management. Some of them hold excess inventories for emergency situations.

This study is hoped to be a useful source for all companies in different business areas struggling against any kind of disruptions. The companies should always be ready and prepared. Thesis subject covers three models and provides a method to calculate the expected risk exposure based on optimal results. Not only disruptions occurrences, but also various cost types within the supply chain network are analyzed and the total cost throughout the supply chain is minimized. The input data, constraints and objective function can be different for every company. This is an adoptable model for single-product, multi-product, single-period or multi-period supply chain networks.

Considering optimal cost results, Model 2 is more costly than Model 1 because there occurs extra costs as inventory holding costs and manufacturing costs. Therefore, it can be concluded that every added cost type has a significant impact on the optimal cost results.

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APPENDIX A

MODEL 1 GAMS CODE

```
Set
    i manufacturers /i1, i2, i3, i4, i5, i6, i7, i8, i9 /
    j warehouses / 1*7 /
    k retailers / k1, k2, k3, k4, k5, k6, k7 /
    s scenarios / s1, s2 /

 Parameters

 b(k) backlog cost of retailer at node k

  / k1 50
    k2 65
    k3 55
    k4 40
    k5 30
    k6 25
    k7 15 /

 Q(i) units of supply from manufacturer at node i

    / i1 470000
      i2 425000
      i3 300000
      i4 410000
      i5 600000
      i6 650000
      i7 436000
      i8 400000
      i9 370000 /

P(j) capacity of warehouse at node j

     / 1 6900
       2 6700
       3 8400
       4 8500
       5 4000
       6 5000
       7 8000 /

d(k) units of demand from retailer at node k

     / k1 3000
       k2 4500
       k3 3000
       k4 2780
       k5 3700
```

```
      k6 5000
      k7 4500 /

f(j) fixed cost of new opened dummy(emergency) facility

    /1 0
     2 0
     3 0
     4 0
     5 100000
     6 150000
     7 170000 / ;

table U(j,k) trust reduction value at node k
    k1 k2 k3 k4 k5 k6 k7
  1 35 27 30 33 26 23 32
  2 24 21 37 34 39 25 22
  3 36 31 28 39 41 20 43
  4 45 24 35 37 22 38 25
  5 21 40 39 37 26 33 31
  6 25 15 43 39 28 23 25
  7 26 27 45 17 37 16 35 ;

table a(s,i) scenario s occurence value on manufacturer node i
       i1 i2 i3 i4 i5 i6 i7 i8 i9
    s1  0  0  1  0  0  0  0  0  0  ;

table a1(s,j) scenario s occurence value on warehouse node j
       1   2   3   4   5   6   7
   s1  0   1   0   0   0   0   0 ;

table g1(j,i) distance from manufacturer node i to warehouse node j
     i1   i2   i3   i4   i5   i6    i7   i8   i9
   1 10    8    2   11    7    5    4    9    3
   2  2    3    4    8    5    9   11    3   12
   3  5    4   11    2    3    6    7   10    9
   4 12   11    7    5    9   15    3    6    4
   5  3    5    8    6    2    9   10    4    7
   6  8    6    5    3    4    7    9   11    2
   7  4    2    6    7   10    3    5    8   11 ;

table g2(k,j) distance from warehouse node j to retailer node k

          1    2    3    4    5    6    7
   k1     8    2    5    6    4    2   11
   k2     7    3    9    2    5    4    8
   k3     5    7    2    3    6    8    4
   k4     4    6    3    4    2    5    7
   k5    11    8    4    7    3    6    2
   k6     2    4    6    5    7    3    9
   k7     6    5    7    4   10    2    3;


variables
X(i,j)
Y(j,k)
 w(i,j) euals 1 if warehouse j is assigned to be served by manufacturer i
 z(j) equals to 1 if warehouse node is open 0 otherwise
```

```
 Variable TC     total expected costs

 POSITIVE VARIABLE X, Y;
 BINARY VARIABLE w, z;

equations
FMCS(i,s) flow from manufacturer to warehouse should conform scenario constraint
FMWS(s,j) flow from warehouse to retailer should conform scenario constraint
DFC(s,j) Dummy flow constraint
PWN(k) Preventing from inventory holding of warehouse node
PMN(j) Preventing from inventory holding of manufacturer node
PBW(j) Preventing from backlogging on warehouse node
WSM(j) Each warehouse is served by only one manufacturer
*RSO each retailer is served by only one warehouse
MCO(s,j) Each warehouse condition to be opened or not depends on the scenario value
MSO(i,j) Manufacturer should be open first to send products.
WSO(j,k) Warehouse should be open first to send products.
KRP(i,s,j) Flow arrangement from manufacturers
ZRP(j,s,k) Flow arrangement from warehouses
*GGG(i,s,j) Not opened manufacturer cannot sent products.


obj   objective function  ;


obj.. TC=e= sum((i,j),g1(j,i)* X(i,j))+sum((j,k),g2(k,j)*Y(j,k))+ sum((j,k),b(k)*(d(k)-Y(j,k)))
+ sum((i,j,k,s), U(j,k)*(a1(s,j)+ a(s,i))) + sum(j, (P(j)**1.2)*z(j));
FMCS(i,s).. sum(j, X(i,j)) =l=  Q(i)*(1-a(s,i));
FMWS(s,j)$(ord(j) lt 5).. sum(k, Y(j,k)) =l=  P(j)*(1-a1(s,j));
DFC(s,j)$(ord(j) gt 4).. sum(k, Y(j,k)) =l= P(j)*z(j);
PWN(k).. sum (j, Y(j,k)) =l= d(k);
PMN(j)..  sum (i, X(i,j)) =l= P(j)*z(j);
PBW(j).. sum (i, X(i,j)) =e= sum (k, Y(j,k));
WSM(j).. sum (i, w(i,j)) =e= 1;
MCO(s,j).. z(j) =l= 1-a1(s,j);
MSO(i,j).. X(i,j) =l= 9999999*w(i,j);
WSO(j,k).. Y(j,k) =l= 9999999*z(j);
KRP(i,s,j)..X(i,j) =l= 9999999*(w(i,j)*(1-a(s,i)));
ZRP(j,s,k)..Y(j,k) =l= 9999999*(z(j)*(1-a1(s,j)));
*RSO(j).. sum ((j), z(j)) =e= 1;
*GGG(i,s,j)..w(i,j) =l= 1-a(s,i);

model network /all/ ;
solve network using mip minimizing TC ;
display X.l, Y.l, z.l, w.l;
```

APPENDIX B

MODEL 2 GAMS CODE

```
Set
   i manufacturers /i1, i2, i3, i4, i5, i6, i7, i8, i9 /
   j warehouses / 1*7 /
   k retailers / k1, k2, k3, k4, k5, k6, k7 /
   s scenarios / s1, s2, s3, s4, s5, s6, s7, s8, s9, s10 /
   t time / t1, t2, t3, t4, t5, t6, t7, t8, t9, t10, t11, t12 /

 Parameters


table b(k,t) backlog cost of retailer at node k at each period of time t
        t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12
   k1 50 40 32 25 17 27 18 51 37 19  47  18
   k2 65 37 51 54 21 18 46 34 44 27  17  57
   k3 55 24 45 36 31 37 55 17 50 33  56  44
   k4 40 19 27 43 52 43 31 22 16 49  39  32
   k5 30 33 37 38 44 51 26 46 31 52  24  26
   k6 25 29 19 49 35 25 47 21 48 37  32  38
   k7 15 41 37 20 45 35 30 38 28 24  43  17 ;

table h(j,t) inventory holding cost at each warehouse node j at each period of time t
      t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12
   1 0  0  10 0 0   0   0  0  4  0   0   0
   2 0  5  0  3  6   0   0  0  0  0   0   0
   3 0  0  2  0  0   0   0  0  6  0   0   0
   4 0  7  0  4  0  17  0  0  0  0  0  20
   5 0  0  7  0  11 15 0  0  9  0  0  15
   6 0  0  0  0  0   0   0  0  0  0   0   0
   7 0  0  0  0  0   0   0  0  0  0   0   0 ;

table E(i,t) manufacturing cost at each manufacturer node i at each period of time t
       t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12
    i1 20 30 35 25 27 40 33 23 25 35  40  21
    i2 33 21 15 24 28 36 21 38 18 39  25  27
    i3 15 26 22 31 29 17 40 31 35 17  19  24
    i4 30 16 14 19 20 25 33 28 34 19  23  28
    i5 17 19 20 34 19 22 27 15 30 24  14  35
    i6 34 12 28 16 29 30 22 27 11 36  24  31
    i7 14 20 15 22 30 19 17 25 22 30  33  18
    i8 20 26 27 23 16 31 28 30 18 21  15  28
    i9 29 19 17 20 15 26 14 22 18 23  27  16 ;
```

```
table Q(i,t) units of supply from manufacturer at node i at each period of time t
                t1     t2             t3            t4          t5          t6       t7            t8          t9        t10    t11    t12
    i1 470000 450000 510000 640000 530000 470000 560000 470000 350000 680000 370000 750000
    i2 425000 350000 480000 540000 460000 600000 640000 620000 630000 640000 450000 610000
    i3 300000 500000 430000 470000 340000 580000 450000 390000 580000 440000 650000 370000
    i4 410000 470000 610000 610000 590000 550000 410000 530000 480000 750000 560000 740000
    i5 600000 350000 590000 390000 730000 340000 370000 570000 610000 510000 380000 550000
    i6 650000 410000 380000 490000 550000 450000 570000 640000 550000 370000 490000 620000
    i7 436000 480000 630000 500000 700000 630000 480000 440000 620000 480000 610000 710000
    i8 400000 600000 450000 760000 380000 750000 610000 560000 640000 560000 670000 580000
    i9 370000 640000 460000 510000 430000 590000 390000 550000 590000 610000 340000 770000
;

table P(j,t) capacity of warehouse at node j at each period of time t
       t1   t2   t3   t4   t5   t6   t7   t8   t9   t10  t11  t12
     1 6900 8400 5700 4300 5700 4400 5300 8400 8500 7900 5900 8100
     2 6700 7500 8100 5100 8000 6300 8200 4200 6100 8200 8100 5800
     3 8400 8100 7200 8600 7200 8400 7900 5100 8200 5900 7800 8800
     4 8500 6100 8500 6700 4900 8200 5900 6300 4600 8300 8500 8400
     5 4000 7400 8700 8000 6200 8000 5600 8100 5900 8000 7000 4900
     6 5000 8100 6800 8100 8200 8100 8500 6500 8100 5500 8100 7100
     7 8000 6400 7500 8500 6100 5700 8400 8300 6800 8200 8300 7100 ;


table d(k,t) units of demand from retailer at node k at each period of time t
        t1   t2   t3   t4   t5   t6   t7   t8   t9   t10   t11 t12
     k1 3000 4100 2500 3000 4000 2000 3000 4000 2300 2700 3300 2400
     k2 4500 3200 3000 2400 2000 3000 2600 2000 2900 3500 2000 2700
     k3 3000 2200 4500 2700 3000 2100 2200 3200 2800 4100 1900 2100
     k4 2780 3500 2100 2800 2100 2900 2500 2100 2500 2000 3600 2000
     k5 3700 4000 3200 2000 2700 3100 2000 2200 3700 1800 2400 3100
     k6 5000 2100 1700 4000 2500 1800 3300 2400 3100 1700 2100 3000
     k7 4500 3400 1200 2900 2300 2400 1200 2300 4000 2300 2100 1400 ;

parameter f(j) fixed cost of new opened dummy(emergency) facility


    /1 0
     2 0
     3 0
     4 0
     5 100000
     6 150000
     7 170000 / ;

table U(j,k) trust reduction value at node k
    k1 k2 k3 k4 k5 k6 k7
  1 35 27 30 33 26 23 32
  2 24 21 37 34 39 25 22
  3 36 31 28 39 41 20 43
  4 45 24 35 37 22 38 25
  5 21 40 39 37 26 33 31
  6 25 15 43 39 28 23 25
  7 26 27 45 17 37 16 35 ;
```

```
table a(s,i,t) scenario s occurence value on manufacturer node i at each period of time t
        t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12
   s1.i1 0  0  0  0  0  0  0  0  0  0   1   1
   s1.i2 1  1  0  0  0  0  0  0  0  0   0   0
   s1.i3 0  1  1  1  0  0  0  0  0  0   0   0
   s1.i4 0  0  0  0  1  1  0  0  0  0   0   0
   s1.i5 0  0  0  0  0  0  0  0  1  1   0   0
   s1.i6 0  0  0  0  0  1  1  0  0  0   0   0
   s1.i7 0  0  1  0  0  0  0  0  0  0   0   0
   s1.i8 0  0  0  0  1  0  0  0  0  0   0   0
   s1.i9 0  0  0  0  0  0  1  1  0  0   0   0 ;

table a1(s,j,t) scenario s occurence value on warehouse node j at each period of time t
          t1 t2 t3 t4 t5 t6 t7 t8 t9 t10 t11 t12
     s1.1 0  1  1  0  0  0  0  0  0  0   0   0
     s1.2 0  0  1  1  1  0  0  0  0  0   0   1
     s1.3 0  0  0  0  1  1  0  0  0  0   0   0
     s1.4 0  0  0  0  0  0  0  1  1  0   0   0
     s1.5 0  0  0  0  0  0  0  0  0  0   0   0
     s1.6 0  0  0  0  0  0  0  0  0  0   0   0
     s1.7 0  0  0  0  0  0  0  0  0  0   0   0 ;

table g1(j,i) distance from manufacturer node i to warehouse node j
     i1   i2   i3   i4   i5   i6   i7   i8   i9
   1  11    8   20    4    7   23    4   22   15
   2  2    3    4    8    5    9   11    3   12
   3  5    4   11    2    3    6    7   10    9
   4  12   11    7    5    9   15    3    6    4
   5  3    5    8    24   2    9   10    4    7
   6  8   20    5    3    4    7    9   11    2
   7  4    2    25   7   10   16   14    8   11 ;

table g2(k,j) distance from warehouse node j to retailer node k
        1    2    3    4    5    6    7
   k1     8    2   12    6    4    2   11
   k2     7    3    9    2   12    4    8
   k3     5    7    2    3    6   22    4
   k4     4    6    3    4   21    1    7
   k5     6   20    4   11    3    6    2
   k6     2   15    6    5    7   11    9
   k7     3    5    7    4    1    2    3 ;

variables
X(i,j,t)
Y(j,k,t)
Inv(j,t) inventory level at warehouse j at time period t
 w(i,j,t) equals 1 if warehouse j is assigned to be served by manufacturer i at time period t
 z(j,t) equals to 1 if warehouse node is open at time period t 0 otherwise

 Variable TC     total expected costs
 POSITIVE VARIABLE X, Y, Inv;
 BINARY VARIABLE w, z;

equations
FMCS(i,s,t) flow from manufacturer to warehouse should conform scenario constraint
FMWS(s,j,t) flow from warehouse to retailer should conform scenario constraint
DFC(s,j,t) Dummy flow constraint
PWN(k,t) Preventing from inventory holding of warehouse node
PMN(j,t) Preventing from inventory holding of manufacturer node
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PBW(j,t) Providing the equality for each warehouse that incomes equals to outcomes including inventory
WSM(j,t) Each warehouse is served by only one manufacturer
MCO(s,j,t) Each warehouse condition to be opened or not depends on the scenario value at each period of time t
MCO1(s,j,t) Recovery period is arranged here as two months of last recovery period not to open disrupted warehouses
MSO(i,j,t) Manufacturer should be open first to send products.
WSO(j,k,t) Warehouse should be open first to send products.
KRP(i,s,j,t) Not opened manufac. cannot be sent products
ZRP(j,s,k,t) Not opened war. cannot be sent products

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obj   objective function  ;
obj..     TC=e=     sum((i,j,t),E(i,t)*X(i,j,t))+     sum((i,j,t),g1(j,i)*     X(i,j,t))+     sum((j,t),f(j)*z(j,t))+
sum((j,k,t),g2(k,j)*Y(j,k,t))+
sum((j,t),h(j,t)*Inv(j,t))+ sum((j,k,t),b(k,t)*(d(k,t)-Y(j,k,t)))
+ sum((i,j,k,s,t), U(j,k)*(a1(s,j,t)+ a(s,i,t))) ;

* sum(j, (P(j,t)**1.2)*z(j,t));   Ekstra objective function equation
FMCS(i,s,t).. sum(j, X(i,j,t)) =l=  Q(i,t)*(1-a(s,i,t));
FMWS(s,j,t)$(ord(j) lt 5).. sum(k, Y(j,k,t)) =l=  P(j,t)*(1-a1(s,j,t));
DFC(s,j,t)$(ord(j) gt 4).. sum(k, Y(j,k,t)) =l= P(j,t)*z(j,t);
PWN(k,t).. sum (j, Y(j,k,t)) =l= d(k,t);
PMN(j,t)..  sum (i, X(i,j,t)) =l= P(j,t)*z(j,t);
PBW(j,t).. sum (i,X(i,j,t))+Inv(j,t-1) =e= sum (k,Y(j,k,t))+Inv(j,t);
WSM(j,t).. sum (i, w(i,j,t)) =e= 1;
MCO(s,j,t).. z(j,t) =l= 1-a1(s,j,t);
MCO1(s,j,t).. z(j,t+1) =l= 1-a1(s,j,t);
MSO(i,j,t).. X(i,j,t) =l= 9999999*w(i,j,t);
WSO(j,k,t).. Y(j,k,t) =l= 9999999*z(j,t);
KRP(i,s,j,t)..X(i,j,t) =l= 9999999*(w(i,j,t)*(1-a(s,i,t)));
ZRP(j,s,k,t)..Y(j,k,t) =l= 9999999*(z(j,t)*(1-a1(s,j,t)));
*RSO(j).. sum ((j), z(j)) =e= 1;


model network /all/ ;
solve network using mip minimizing TC ;
display X.l, Y.l, Inv.l, z.l, w.l;
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